Improving the Luminous Efficacy and Visual Comfort of a Radiant Panel with Integrated Lighting

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ABSTRACT OF THE
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The objective of this thesis was to develop a luminaire, which incorporates heating, ventilation and air conditioning (HVAC). The HVAC features of the luminaire have been developed earlier and this thesis will concentrate solely on improving its luminous efficacy and visual comfort. The aim was to achieve sufficient illumination for typical office lighting while providing visual comfort.

Various methods of improving the luminous efficacy and visual comfort were found, and many of them were implemented in a prototype luminaire. Improvements were achieved through optimizing the following components of the luminaire: the light source, the light guide plate, the reflective back plate, and the diffusing film.

The results show that with these methods, the luminaire can achieve the required levels of illuminance and visual comfort that were aimed for. The greatest improvements in luminous efficacy were found to come from alternative light-emitting diode (LED) packages and the reflective back plate. An increase in visual comfort was achieved through a more uniform luminance distribution and simulations were used to evaluate the amount of glare produced by the luminaire.

Keywords:
LED lighting, solid-state lighting, luminaire, luminous efficacy, visual comfort

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Työn tavoitteena oli kehittää valaisinta, jossa on integroitu lämmitys-, jäähdytys- ja ilmankiertojärjestelmä. Lämmitys-, jäähdytys- ja ilmankiertojärjestelmä on kehitetty jo aikaisemmin ja tämä työ keskittyykin vain ja ainoastaan valaisimen valotehokkuuden ja näkömukavuuden parantamiseen. Tavoitteena oli saada riittävä valaistusvoimakkuus tavalliseen toimistotyöhuoneeseen luoden samalla näkömukavuutta.

Työssä löydettiin useita keinoja parantaa valotehokkuutta ja näkömukavuutta, ja monta näistä hyödynnettiin valaisimen kehittämisessä. Parannuksia tehtiin optimoimalla seuraavia komponentteja: valonlähde, valonohjauslevy, heijastava taustalevy ja hajottava etulevy.

Näitä keinoja hyödyntämällä saavutettiin haluttu valaistusvoimakkuus ja näkömukavuus tavallisessa toimistohuoneessa. Huomattavimmat parannukset valotehokkuuteen saatiin vaihtoehtoisista valonlähteistä ja heijastavasta taustalevystä. Näkömukavuutta parannettiin tasaisemman luminanssijakauman kautta ja valaisimen aiheuttaman häikäisyn taso todennettiin simuloinneilla.

Avainsanat:
LED valaistus, puolijohdevalaistus, valaisin, valotehokkuus, näkömukavuus

Preface

This thesis was written between May and October 2016 while working for and learning from the experts on illumination at Aalto University Department of Electrical Engineering and Automation. This work is part of a long project by Caverion Suomi Oy, which has already employed a few theses before mine both in Finland and abroad.

I would like to thank Caverion for giving me the opportunity to be in such a responsible position in developing this next-generation luminaire. I would also like to thank my supervisor Prof. Liisa Halonen for her invaluable guidance throughout this process and an illuminating insight into the world of lighting. Also invaluable was the assistance and feedback I got from my advisors Pramod Bhusal D.Sc. (Tech.) and Paulo Pinho D.Sc. (Tech.). There are numerous other people who also deserve my highest commendation for their support and suggestions, including Eino, Mikko, Shiyong, Rupak and last, but not least, Sonia.

This thesis is the final step in finishing my studies, which makes me reflect on all the years I have spent here within the confines of Otaniemi. It makes me a little sad having to leave all this behind, but also excited to leap into whatever challenges face me next with the newfound knowledge this university has given me. The greatest thanks for these years go to the friends and family that have supported me.

Espoo, Finland
October 7th, 2016

Antti Eerola

Contents

Abbreviations and Symbols

Abbreviations

BLU	Back-light unit
CCT	Correlated colour temperature
CE	Conformité Européenne
CIE	Commission Internationale de L'Eclairage, International Commission on Illumination
CRI	Colour rendering index
EU	European Union
HVAC	Heating, ventilation and air conditioning
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
LCD	Liquid crystal display
LED	Light-emitting diode
LGP	Light guide plate
PCB	Printed circuit board
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
PS	Polystyrene
SSL	Solid-state lighting
TIR	Total internal reflection
UGR	Unified glare rating

Symbols

A	Surface area normal to heat flow
A_{Irel}	Area underneath the curve of I_{rel}
A_{T*Irel}	Area underneath the curve of $T * I_{rel}$
C	Half-plane in the C, γ coordinate system
E_b	Illuminance in the plane of the eye, excluding the glare source
E_m	Maintained illuminance
I_F	Forward current
I_{rel}	Relative luminous intensity
I_V	Luminous intensity
I_{VO}	Luminous intensity at the optical beam axis
k	Thermal conductivity
$K_{\eta IF}$	Coefficient for change of luminous efficacy with forward current
$K_{\eta O}$	Total reflective loss coefficient
$K_{\eta O120}$	Coefficient for optical losses at a beam angle of 120 degrees
$K_{\eta O150}$	Coefficient for optical losses at a beam angle of 150 degrees
$K_{\eta T}$	Coefficient for change of luminous efficacy with temperature

$K_{\eta T80}$	Coefficient for change of luminous efficacy with temperature at 80 °C
L	Luminance of the glare source
n_1	Refractive index of air
n_2	Refractive index of acrylic
P	Power
p	position index of the glare source
Q	Power dissipated by one LED
R	Reflectance
r	Radius
R_a	Colour rendering index
R_p	Reflectance for p-polarised light
R_s	Reflectance for s-polarised light
R_θ	Thermal resistance
$R_{\theta Al}$	Thermal resistance of the luminaire frame
$R_{\theta Cu}$	Thermal resistance of the copper piping
$R_{\theta JS}$	Thermal resistance from the junction to the solder point of an LED package
$R_{\theta PCB}$	Thermal resistance of the PCB
T	Transmittance
T_a	Ambient temperature
T_{cp}	Correlated colour temperature
T_j	Junction temperature
T_w	Water temperature
U_0	Illuminance uniformity
V	Voltage
x	Thickness of part parallel to heat flow
X	Column number
α	Angle of observation
γ	Measurement angle in the C, γ coordinate system
η	Luminous efficacy
η_{calc}	Calculated luminous efficacy
η_{eff}	Effective luminous efficacy
θ	Beam angle
θ_i	Angle of incident light
θ_t	Angle of transmitted light
ΣR_θ	Sum of thermal resistances
Φ_e	Total radiant flux
Φ_V	Luminous flux
Φ_{Vrel}	Relative luminous flux
ω	Solid angle of the glare source at the eye

1 Introduction

In the last decade, light-emitting diodes (LEDs) have become increasingly popular as light sources in luminaires. This may be due to their significant increase in luminous efficacy as shown by the U.S. Department of Energy's Solid-State Lighting (SSL) research and development plan [1]. Another reason for this could be the small size of LED packages, which enables improved optical control and directionality. Compared to traditional light sources, LEDs also have a higher level of performance when it comes to rated life, colour adjustment and related control gear [2]. This means that luminaire manufacturers have more freedom in designing their products.

Caverion Suomi Oy has chosen to utilize this freedom by developing a luminaire operating on a principle similar to that of backlight units in liquid crystal displays: an LED light source illuminates the sides of a light guide plate (LGP), which distributes the light and emits it in one direction. What makes this luminaire special is that it incorporates heating, ventilation and air conditioning (HVAC) as well.

The HVAC properties of this luminaire have been developed already and a patent has been filed for the luminaire. Previous measurements by Caverion have proved the functionality of the HVAC part and the current issue is in developing the lighting components.

1.1 Requirements and EU Regulations

Caverion has set strict requirements on the luminaire: it must have even light distribution on the surface of the luminaire, its luminous efficacy should be around 100 lm/W, it must provide visual comfort and also comply with current EU regulations so that it will be eligible for the CE marking. The correlated colour temperature (CCT) of the luminaire should be around 4000 K and the appearance of the luminaire when switched off should be white. The requirements will be addressed in their relevant chapters, while this chapter will briefly go through the EU regulations to be fulfilled by this product.

To be sold in the European Union, the luminaire needs to have a CE marking. This marking is granted to products which comply with relevant regulations. Indoor lighting regulations are outlined in the European Standard EN 12464-1:2011 "Light and lighting. Lighting of work places. Part 1: Indoor work places" [3]. The standard defines all aspects of lighting of indoor spaces, but this thesis will concentrate on the parts that can be affected by luminaire design.

Most of these regulations are dependent on the installation location of the luminaire, so this thesis will look at that of a typical office environment. One regulated quality of the environment is glare. This can be divided into disability glare and discomfort glare. The former seldom exists without the latter in interior workplaces, so the regulations are based on limiting discomfort glare. This is quantified by the Unified Glare Rating (UGR), which will be studied in chapter 2.4. The limit for UGR for typical office conditions has a value of 19. [3]

Illuminance also needs to be at a specified level in office environments. The standard defines this as the minimum maintained illuminance E_m at working surfaces with a minimum illuminance uniformity U_0. Illuminance uniformity is the ratio of the minimum illuminance to the average illuminance at the task area. In tasks of writing, typing, reading and data processing, E_m has a value of 500 lx with a minimum illuminance uniformity U_0 of 0.6. In tasks of filing, copying, etc. these limits are 300 lx and 0.4, respectively. [3]

Flicker is another aspect which may cause visual discomfort and needs to be minimized [3]. This is the sensation caused by a luminance or a spectral distribution fluctuating with time [4]. In LED lighting, flicker results from alternation of the LED driver output current [5]. This thesis will not concentrate on development of the LED driver, so flicker will not be studied further.

Other qualities to look at are the CCT and the colour rendering index (CRI). According to the standard [3], setting the CCT to over 4000 K complies with most environments, as does a CRI of over 80. Also a maintenance schedule for the luminaire needs to be defined, which in this case is simply its rated life. [3]

1.2 Objectives and Limitations

This thesis aims to improve the luminous efficacy of the luminaire and ensure there is no visual discomfort while paying close attention to its aesthetic properties as well. The main target will be achieving a luminous efficacy close to 100 lm/W. Chapters 2.2 and 2.3 will be dealing with the theory behind parts of the luminaire that affect this.

The visual comfort of the luminaire will also be improved. This means reducing the glare caused by it and ensuring that the luminaire looks pleasant while providing adequate lighting. These aspects will be looked at in more detail in chapter 2.4.

While the main emphasis is on developing the lighting properties of this luminaire, the radiant properties of the panel cannot be omitted completely. Since this panel also needs to have HVAC functionality, modifications are limited to certain parts of the luminaire. This thesis will not, however, attempt to develop the radiant features of the panel, unless they are so closely linked to the lighting properties that they need to be considered.

2 Radiant Panel with Integrated Lighting

This chapter focuses on the theoretical basis behind the choice of parts for the luminaire. The first section is about the panel. This means the whole device with radiant parts and the luminaire together. The following sections are concerned with the theory behind the various components that make up the luminaire and why these components have been chosen. The main focus when choosing these components is on improving luminous efficacy. The final section is on improving the visual comfort and aesthetics of the luminaire.

2.1 Integrating Lighting and Temperature Control

The panel being developed incorporates a luminaire and radiant heating, cooling and air circulation into one device. The radiant components of the panel work by circulating water inside copper piping on the backside of the panel, as shown in Figure 1. The water remains between 16 °C and 40 °C depending on how much cooling or heating power is required. The radiant properties of the panel have already been tested by Caverion.

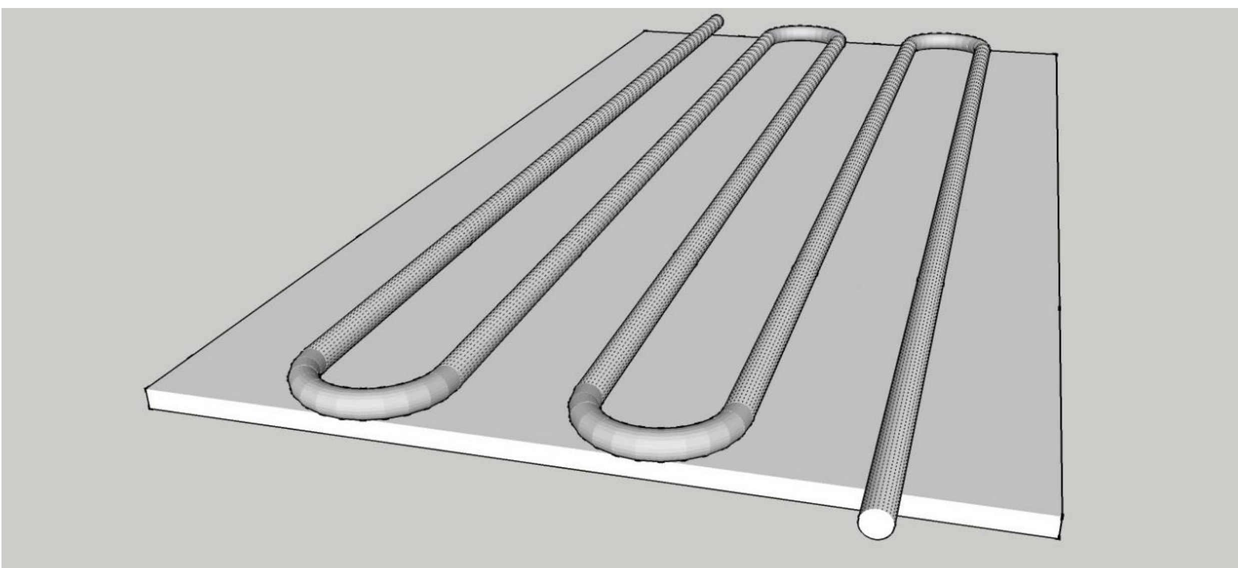

Figure 1: Diagram of copper piping on top of the luminaire.

The challenge is integrating lighting to this panel. The luminaire is below the piping so it has to be thin to allow for good radiant properties. It employs a similar method for distributing light as the backlight units in liquid crystal displays (LCD). The LEDs are placed in strips, which transmit light into the LGP from the side. The light is then transmitted via total internal reflection until it is emitted downwards out of the LGP. Part of the light will also be emitted upwards, but will then be reflected by the reflective back plate. [6] [7] The operating principle will be described in further detail in chapter 2.3. A cross-section of the radiant panel with the aforementioned components is presented in Figure 2.

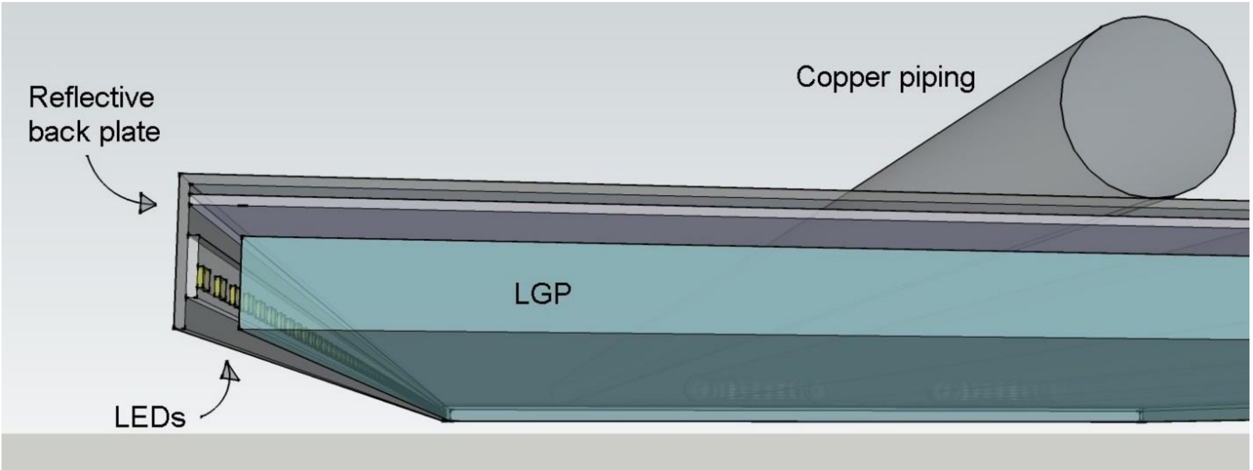

Figure 2: Cross-section of the radiant panel.

2.2 Light Source

The light source chosen for this luminaire is an LED package (OSRAM Opto Semiconductors, DURIS S2, Germany) integrated into an LED module. This LED package has been developed for indoor general lighting applications and provides high light output and a wide viewing angle in a small package size. [8] This subchapter will focus on the technical characteristics of this LED which are relevant for luminaire design. Other LEDs will be suggested as possible replacements, and an appropriate comparison will be made.

Based on the objectives defined in chapter 1.2, there are three points of interest in an LED package for the luminaire being developed: correlated colour temperature (CCT) T_{cp}, luminous efficacy η and beam angle θ. The luminous efficacy and the beam angle of the LED package will have an effect on the luminous efficacy of the luminaire. However, the luminous efficacy stated by the LED manufacturer cannot be taken at face value, since it has been measured in a controlled laboratory environment and not in realistic operating conditions. This chapter will obtain coefficients that can be used to calculate a more accurate value for η, which will be called the effective luminous efficacy of the light source η_{eff}.

2.2.1 Correlated Colour Temperature

The CCT is the temperature of a blackbody radiator whose chromaticity most closely matches that of the source [4] [9] [10] [11] [12]. The CCT will be determined by measurement as described in chapter 3. Fotios [13] and Baniya et al. [14] suggest that 4000 K is the preferred CCT for office lighting. Correspondingly the requirement for the CCT set by Caverion is approximately 4000 K. The DURIS S2 LED package fulfils the requirement according to the datasheet [8] and this is also determined by measurement in chapter 3.

2.2.2 Luminous Efficacy

The luminous efficacy of a light source is the ratio of the total luminous flux Φ_V to the total input power P [4] [9]. The luminous efficacy of the LED package will have a significant effect on the luminous efficacy of the luminaire, so its dependency on various factors will be studied. This value is also stated by the manufacturer in the datasheet of the LED (159 lm/W for the DURIS S2 [8]), but varies with time, junction temperature T_j and forward current I_F. The luminous efficacy of the light source is measured in chapter 3.

Forward current affects the luminous flux of the LED, but its luminous efficacy only marginally, since it is proportional to the luminous flux, but inversely proportional to the forward current as follows:

$$\eta = \frac{\Phi_V}{P} \propto \frac{\Phi_V}{I_F}. \qquad (1)$$

The slightly unideal properties of the p-n junction can be seen in Figure 3, which shows the relative luminous flux Φ_{Vrel} versus forward current. In Figure 3 the relative luminous flux is relative to the nominal forward current of 65 mA. The gradient of the curve is not constant (red line tangential at 65 mA represents constant luminous efficacy) and as the current increases, the rate of change of luminous flux decreases. Thus the luminous efficacy decreases marginally as the forward current increases. Considering the above, in this thesis, the forward current shall be kept constant at its recommended operating value of 65 mA and the coefficient for change of luminous efficacy with forward current is $K_{\eta I_F} = 1$.

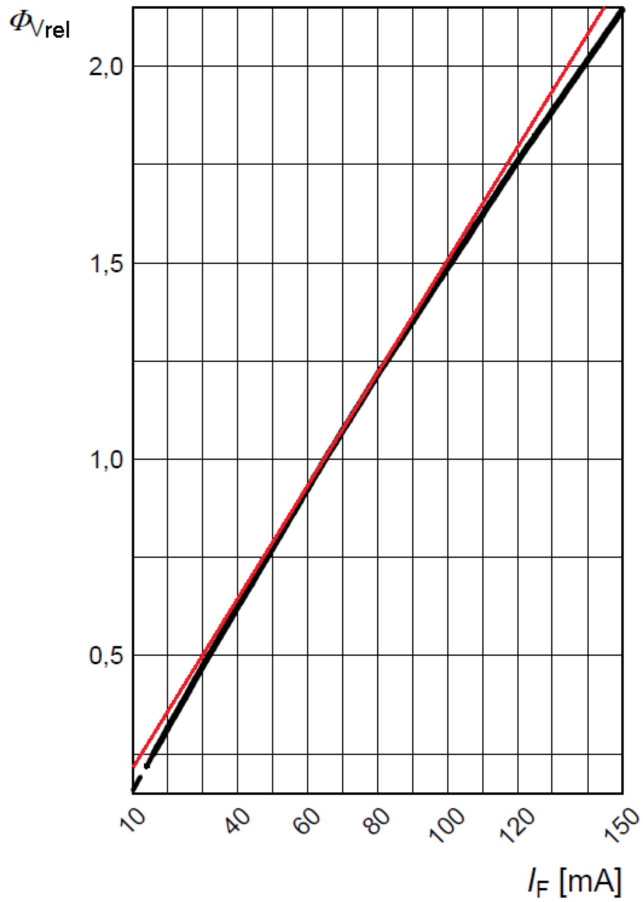

Figure 3: Relative luminous flux Φ_{Vrel} versus forward current I_F. T_j = 25 °C. [8]

The luminous flux is also related to the operating temperature of the p-n junction. Thus the junction temperature also affects the luminous efficacy. As the junction temperature increases, the luminous flux decreases [9]. This relationship is presented in Figure 4 as the relative luminous flux changing with temperature at a forward current of 65 mA. In Figure 4 the relative luminous flux Φ_{Vrel} is relative to the nominal junction temperature of 25 °C. The junction temperature seems to have a significant effect, since it might be as high as 80 °C resulting in a nearly 10% decrease in luminous flux from that of the nominal junction temperature of 25 °C. This must be taken into account when measuring the luminous efficacy of the LED packages without the luminaire as a heat sink.

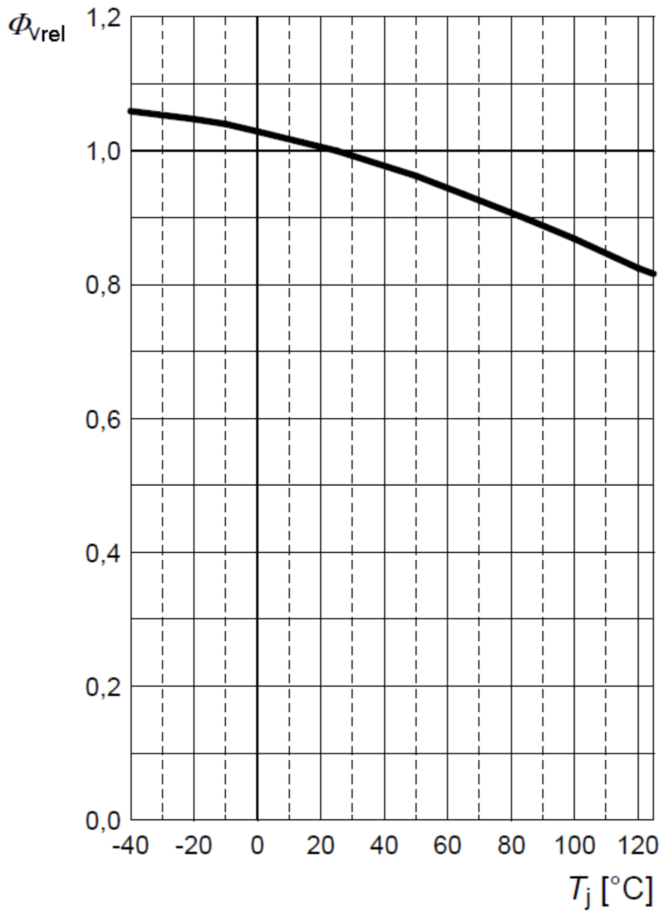

Figure 4: Relative luminous flux Φ_{Vrel} versus junction temperature T_j. I_F = 65 mA [8]

In real operating conditions, however, the junction temperature will stay lower, as the LEDs are cooled by the circulating water of the HVAC system, which is between 16 °C and 40 °C. In the final product the copper piping will reside behind the LED modules. To estimate the junction temperature in real operating conditions, a simplified thermal model is created for one LED package. The LED transmits most of its heat via conduction through the printed circuit board (PCB), the luminaire frame and copper piping to the circulating water. The thermal resistances R_θ of these parts can be calculated when we know their physical size and thermal conductivity k, as follows:

$$R_\theta = \frac{x}{A * k}, \tag{2}$$

where x is the thickness of the part parallel to heat flow, and A is the surface area normal to the heat flow [15]. The size of the LED module and luminaire behind a single LED package is measured and the PCB material is assumed to be a common glass fibre resin FR4. The properties of these parts are as in Table 1.

Table 1: Thermal properties of luminaire components.

Material	Thermal conductivity, k [W/mK]	Thickness, x [m]	Surface area, A [m²]	Thermal resistance, R_θ [K/W]
PCB FR4	0.25 [16]	1.6E-3	6.25E-5	102.4
Aluminium	205 [15]	1.5E-3	6.25E-5	0.12
Copper	385 [15]	1E-3	3.75E-5	0.07

The heat flow can be modelled by an equivalent circuit, where dissipated power is represented by a current source, temperatures are represented by voltages and thermal resistances by resistors. The simplified model is shown in Figure 5, where Q is the power dissipated by one LED, T_w is the water temperature, $R_{\theta JS}$ is the thermal resistance from the junction to the solder point, $R_{\theta PCB}$ is the thermal resistance of the PCB, $R_{\theta Al}$ is the thermal resistance of the luminaire frame and $R_{\theta Cu}$ is the thermal resistance of the copper piping. This model assumes that all the heat generated by the LED is conducted to the circulating water, which is at constant temperature, and that the connections between the different materials are perfect conductors of heat.

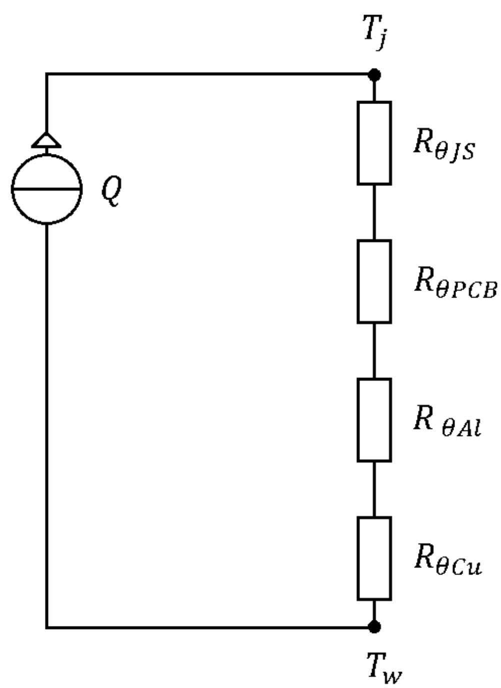

Figure 5: A simplified thermal model of one LED in the luminaire with dissipated power Q, temperatures T and thermal resistances R_θ.

Q and $R_{\theta JS}$ are obtained from the LED datasheet as $0.1885\ W$ and $24\ K/W$, respectively [8]. The junction temperature is then

$$T_j = T_w + Q\ \Sigma R_\theta, \tag{3}$$

where ΣR_θ is the sum of the thermal resistances. Thus the real junction temperature is 39.9 °C and 63.9 °C calculated at water temperatures of 16 °C and 40 °C, respectively. This means that according to Figure

4, the luminous flux will stay within 6% of its nominal value. Therefore, the coefficient for change of luminous efficacy with temperature is $K_{\eta T} = 0.94 \ldots 0.98$, depending on the water temperature. When measuring the luminous efficacy of the luminaire in chapter 3, the HVAC part will not however be functional, and T_j will be estimated to be 80 °C. Thus the coefficient for the DURIS S2 package will be $K_{\eta T80} = 0.91$.

2.2.3 Beam Angle

The beam angle θ of the LED also makes a difference on how the light emitted by it is transmitted into the light guide plate (LGP). The beam angle θ is defined as the angle between two imaginary lines in a plane through the optical beam axis, such that these lines pass through the centre of the front face of the lamp and through points at which the luminous intensity I_V is 50% of the optical beam axis intensity I_{VO} [17]. This is presented in Figure 6.

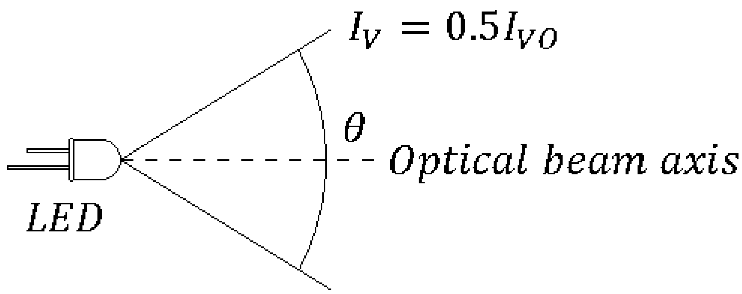

Figure 6: Beam angle θ of an LED at which luminous intensity I_V is 50% of the optical beam axis intensity I_{VO}.

A wider beam angle seems to be a logical choice for a uniform distribution of light on the surface of the LGP, which will be studied further in subchapter 2.4. However, a narrower beam angle causes less light to be reflected from the boundary between the LED package and the LGP, as shown by the Fresnel equations [18], and results in better luminous efficacy of the luminaire. The beam angle of the DURIS S2 is stated to be 150 degrees, which is wide, and it is expected to reduce the luminous efficacy of the luminaire.

It is possible, but impractical, to mathematically calculate the effect the beam angle has on the luminous efficacy of the luminaire, since the only source of data for the light source intensity with respect to the angle of observation is the measurement results from the light source manufacturer shown in Figure 7 [8]. The reflectance at the LGP boundary can be calculated using the Fresnel equations as follows for polarized light:

$$R_s = \left| \frac{n_1 cos\theta_i - n_2 \sqrt{\left(1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2\right)}}{n_1 cos\theta_i + n_2 \sqrt{\left(1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2\right)}} \right|^2 \tag{4}$$

$$R_p = \left| \frac{n_1 \sqrt{\left(1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2\right)} - n_2 cos\theta_i}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} sin\theta_i\right)^2} + n_2 cos\theta_i} \right|^2, \tag{5}$$

where R_s is the reflectance for s-polarised light, R_p is the reflectance for p-polarised light, n_1 is the refractive index of air, n_2 is the refractive index of acrylic (1.4905 at 589.3 nm [15]) and θ_i is the angle of incident light. Equations 2 and 3 have been simplified with Snell's law, so that knowledge of the angle of transmission θ_t is not necessary. Assuming the incident light is unpolarised, the total reflectance is

$$R = \frac{1}{2}\left(R_s + R_p\right). \tag{6}$$

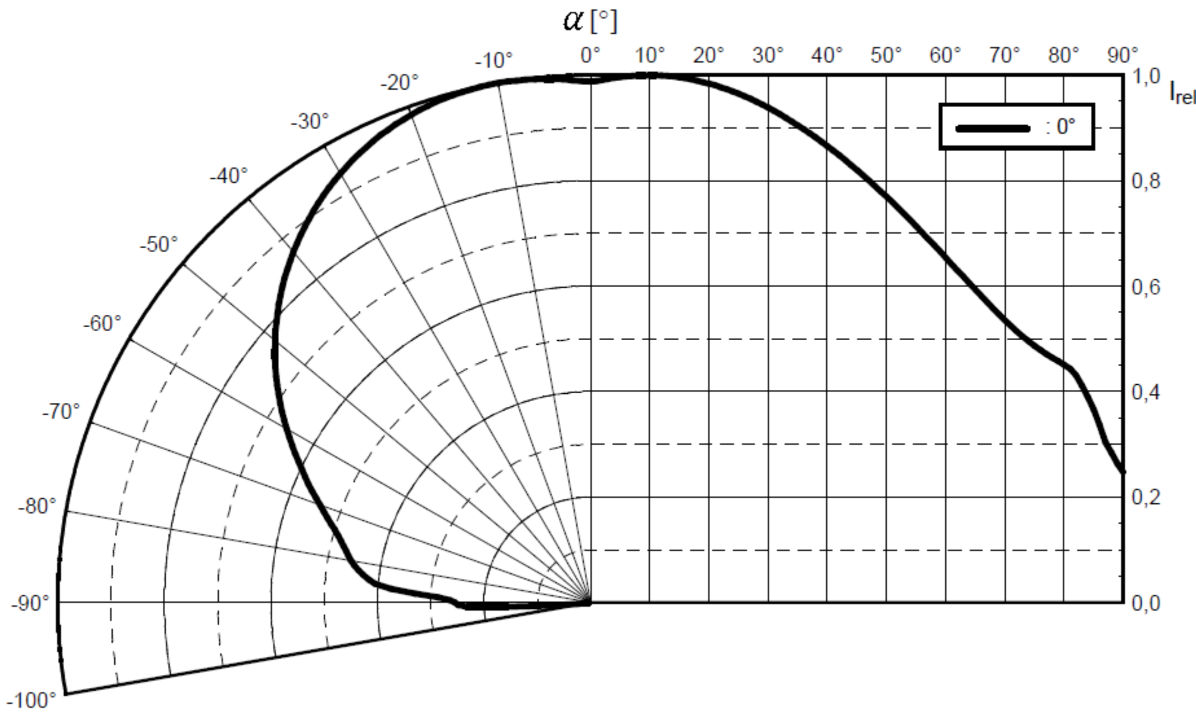

Figure 7: Relative luminous intensity I_{rel} versus angle of observation α [8].

Due to the conservation of energy, the sum of transmitted and reflected light must be equal to the amount of incident light, and thus the sum of the coefficients for reflectance R and transmittance T is equal to 1 [18]. The relative luminous intensity I_{rel}, the total transmittance T and their product $T * I_{rel}$ are plotted in Figure 8 versus the angle of observation α. The portion of light reflected back at the LGP boundary, i.e. the total reflective loss coefficient $K_{\eta O}$ can be calculated as:

$$K_{\eta O} = \frac{A_{T*I_{rel}}}{A_{I_{rel}}}, \tag{7}$$

where $A_{T*I_{rel}}$ is the area underneath the curve of $T * I_{rel}$ and $A_{I_{rel}}$ is the area underneath the curve of I_{rel}.

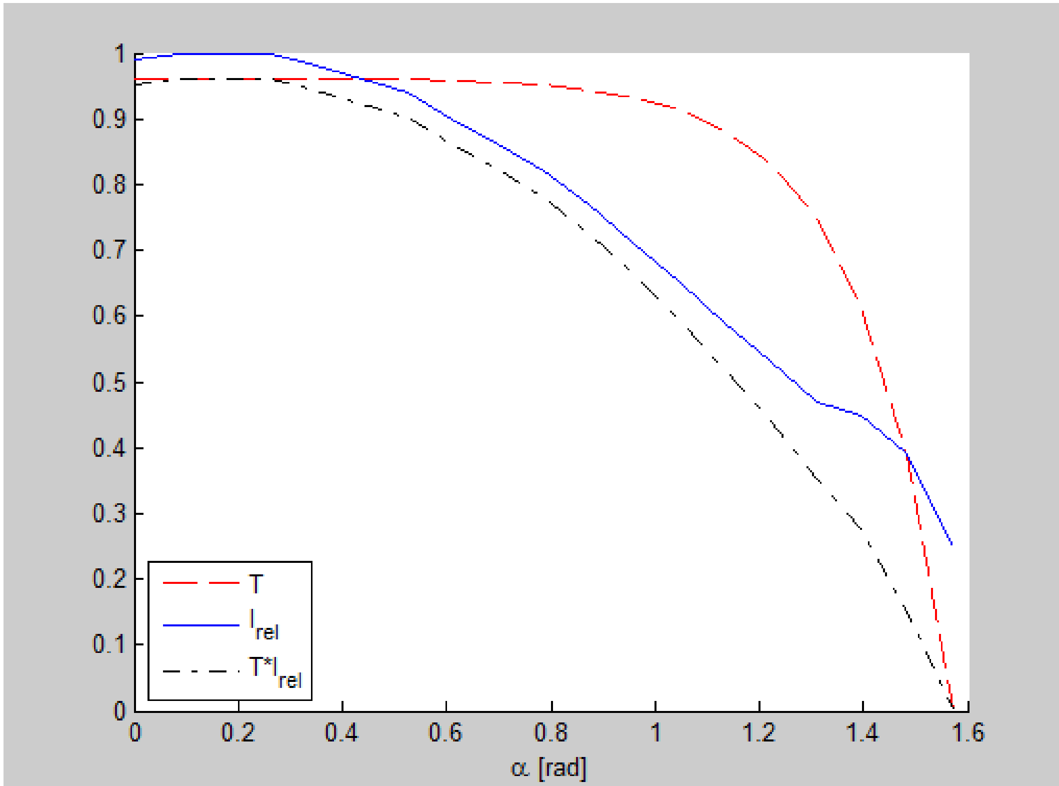

Figure 8: Relative luminous intensity I_{rel} of the DURIS S2 LED package, total transmittance T at the LGP boundary and their product $T * I_{rel}$ versus angle of observation α.

This assumes incorrectly that the incident surface is perfectly smooth and is only an approximation based on graphed data from the LED manufacturer. Thus, this should only be used as a rough estimate of the optical losses in this boundary. The coefficient of optical losses for this boundary is obtained as $K_{\eta O150} \approx 0.903$.

It is easily deduced that with a narrower beam angle the losses are lower, since transmittance decreases with the angle of observation α. With a beam angle of 115 degrees, as in a Samsung LED package (Samsung, LM561C, South Korea), this coefficient could be up to $K_{\eta O115} \approx 0.942$.

2.2.4 Alternative LED packages

LED packages are available from other manufacturers as well. This chapter will make a brief comparison of LEDs with similar photometric characteristics to the OSRAM DURIS S2 and an evaluation will be made on which package would be the most suitable for this luminaire using coefficients calculated as above. The LEDs chosen for comparison are all from well-known brands to ensure availability and accuracy of measurement data. The CCT of all LEDs is around 4000 K and the size of the packages is close to one another. The LEDs along with their appropriate properties are presented in Table 2. The effective luminous efficacy η_{eff} is calculated by multiplying the manufacturer's luminous efficacy by the optical and thermal coefficients $K_{\eta O}$ and $K_{\eta T80}$, respectively.

Table 2: Alternative LED packages.

LED package	CCT, T_{cp} [K]	Beam angle, θ [deg]	Luminous efficacy, η [lm/W]	$K_{\eta O}$	$K_{\eta T80}$	effective luminous efficacy, η_{eff} [lm/W]
OSRAM DURIS S2 [8]	4000	150	170	0.903	0.91	140
OSRAM DURIS S5 [19]	4000	120	160	0.939	0.91	137
OSRAM DURIS E5 [20]	4000	120	178	0.939	0.91	152
Nichia NF2W757G-V1F1 R8000 [21]	5000	116	210	0.939	0.93	183
Nichia NF2L757G-V1F1 R8000 [22]	3000	116	189	0.939	0.94	167
Lumileds Luxeon 3535L HE [23]	4000	115	190	0.937	0.91	162
Lumileds Luxeon 3020 [24]	4000	110	153	0.938	0.90	129
Lumileds Luxeon 3030 2D [25]	4000	116	155	0.938	0.90	131
Cree XLamp XH-B [26]	4000	130	117	0.918	0.90	97
Cree XLamp XH-G [27]	4000	130	142	0.921	0.90	118
Samsung LM301A SF [28]	4000	115	153	0.942	1.01	146
Samsung LM302A [29]	4000	115	128	0.942	0.90	109
Samsung LM281A [30]	4000	120	129	0.940	0.90	109
Samsung LM561C [31]	4000	115	196	0.942	0.92	170
Samsung LM561B Plus S5 [32]	4000	115	183	0.942	0.92	159
Citizen Citiled CLL130 [33]	4000	110	128	0.940	0.90	108

As can be seen, the fourth package in Table 2 (Nichia, NF2W757G-V1F1 R8000, Japan) seems to be by far the best option while the *DURIS S2* has only 77 % of its effective luminous efficacy. However, the CCT of the *Nichia* LED is high at 5000 K and so a better choice would be for example the *Samsung* (Samsung, LM561C, South Korea) or the *Lumileds* (Lumileds, Luxeon 3535L HE, United States). The last LED package here (Citizen Electronics, Citiled CLL130-0101B2, Japan) is the one preinstalled in the prototype luminaire. This will be used as a reference in developing other components of the luminaire.

Also of importance is the fact that the beam angle gives merely an indication of the coefficient for optical efficiency. The coefficient takes into account the whole luminous intensity distribution while the beam angle only states the angle of observation at which the luminous intensity is 50% of the centre beam intensity. Thus it is possible that a package with a wider beam angle would have a high $K_{\eta O}$.

2.3 Optical Components

This subchapter is about the optical components of the luminaire. This means the components involved in guiding, transmitting, reflecting and diffusing light emitted by the light source. These include a light guide plate (LGP), a reflective back plate and a diffusing film on top. This arrangement is very similar to many edge-lit back-light units (BLU) used in liquid crystal display (LCD) panels. [6] [7] This subchapter will go through these components of the luminaire explaining how they function, and present different possibilities for these parts.

2.3.1 Light Guide Plate

The function of the LGP is to distribute light from the source uniformly over the surface of the plate [34] [6] [7]. The light rays from the source on the edge of the LGP experience total internal reflection (TIR) while traveling in the LGP. Eventually they hit the light-scattering pattern on the bottom-side of the LGP, which has a higher refractive index. This causes the light rays to emanate from the LGP either towards the diffusing film or towards the back plate [6] [35] [7] [36] as shown in Figure 9. Typically the LGP is made of polymethyl methacrylate (PMMA), also known as acrylic glass [7]. In LCD BLUs the LGP is often wedge-shaped (as in Figure 9) to provide uniform light distribution when the light source is only on one side. In the luminaire being developed, LEDs are located on both sides, so the LGP is of uniform thickness. The operating principle remains unchanged.

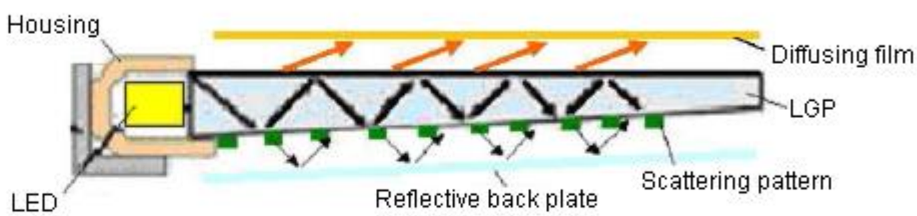

Figure 9: Light rays traveling in the optical components [7].

The light-scattering pattern is usually either a dot-pattern or a prism-pattern formed by V-shaped grooves [34] [6]. Sometimes this can also be a microlens-pattern or a powder-blasted texture [7]. The prism-pattern has the function of condensing light, thus providing higher brightness than the scattering dot LGP [6]. The dot-patterns are either laser-etched, silk-screened or printed onto the surface of the LGP. Different patterns are presented in Figure 10, the dot-pattern and V-shaped groove prism pattern being the most common ones. The light source is on the left and the LGP emits light downwards. The patterns are not to scale.

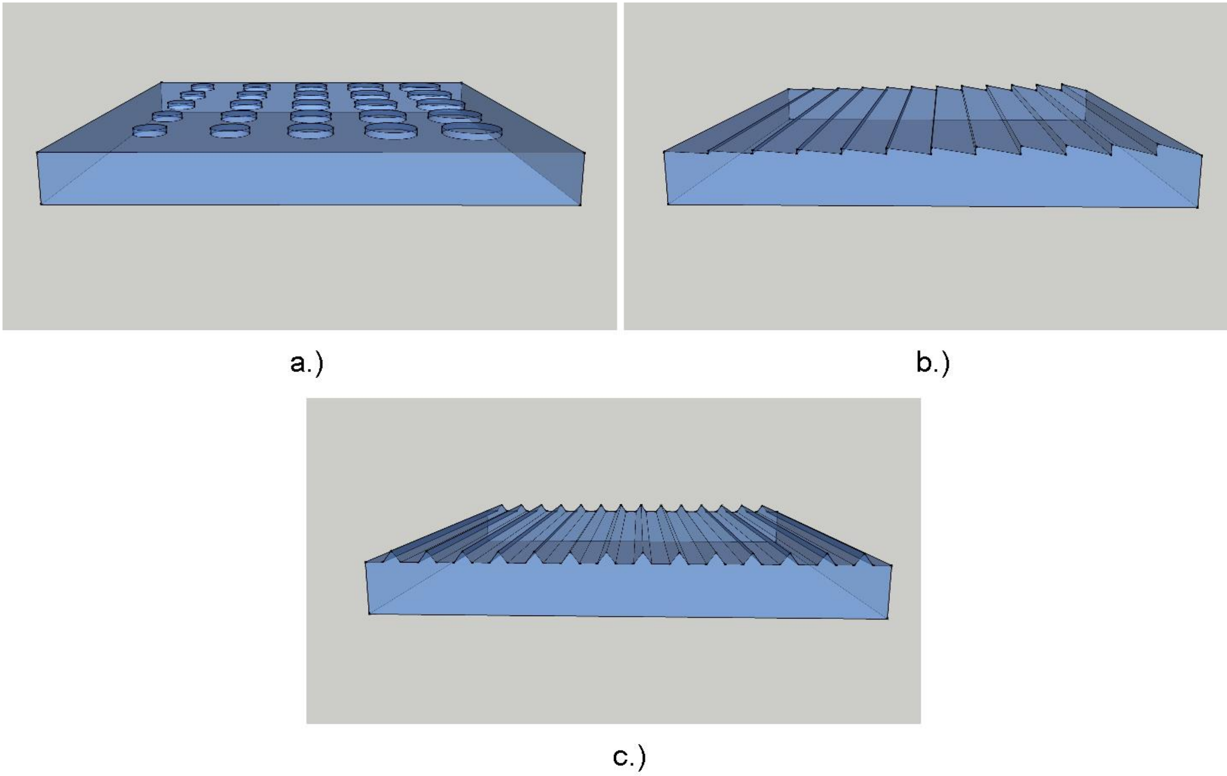

Figure 10: Light-scattering patterns. a.) dot-pattern, b.) V-shaped groove prism pattern, c.) prism pattern. The light source is on the left and the LGP emits light downwards.

Brightness of light emitted to the panel from the edge decreases with distance from the light source. This means the density of the pattern must vary as a function of distance from the LED. [34] [6] [35] [7] [36] The distribution of light in the prism design depends on prism angle, spacing and width of prism [6]. This is shown in Figure 10b. Dot-patterns and microlenses are preferred, because it is easy to adjust luminance uniformity by changing the dot or lens radius [7]. In Yu et al.'s [34] dot-pattern design, the dots are arranged in rows and columns and the dot radius r changes with column number X (starting from the light source) as in equation 6:

$$r = A + BX + CX^2 + DX^3 + EX^4 + FX^5, \quad (8)$$

where A-F are constants determined by dimensions of the LGP and are between 1 and 9. Thus, the dot radius must increase further from the light source, as in Figure 10a. However, designing the optics of an optimal LGP is not within the scope of this thesis and will not be studied further. It suffices to know how these function to be able to compare the suggested LGPs.

To prevent light escaping to the non-illuminated sides of the LGP, it is suggested to attach a reflective surface to those edges [37] [35]. Due to the proportionally small size of these reflectors, too much time will not be used studying different reflective materials for this.

According to Altuglas International [38], the absorption of light in acrylic is negligible. Thus the thickness of the LGP has very little effect on its optical properties. A thinner LGP may make it more difficult to align the LGP with the LEDs and lessen the amount of light transmitted into the LGP. However, the thickness has an effect on the radiant properties of the panel, since it acts as an insulator. This will not be studied further in this thesis, but a thinner LGP would be a better conductor of heat and a better choice for this luminaire.

The various LGPs suggested for this luminaire are presented in Table 3, along with their respective properties. Their performance depends mostly on the effectiveness of their light-scattering patterns and will be evaluated in chapter 3 by measurement.

Table 3: Comparison of LGPs.

Name	Type	Thickness [mm]	Material
Caverion prototype LGP	Laser-etched ellipsoidal dot-pattern on rear face	5	PMMA
Yongtek LGP [39]	Laser-etched pattern on one face, linear pattern on other face	3	PMMA
A.L.P. Europe Sewon RD90 LGP [40]	Laser-etched dot-pattern on one face, linear micro-pattern on other face	3	PMMA

2.3.2 Reflective Back Plate

As mentioned previously, part of the light escapes to the rear of the LGP from the light-scattering pattern. The function of the back plate (see Figure 9, page 13) is to reflect light back to the LGP. [35] [7] This means that the reflective back plate must have a reflectance that is as high as possible. To achieve an even distribution of light on the surface of the LGP, the reflection should also be diffuse. Possibilities for the reflective back plate are briefly described here and summarized in Table 4.

Aluminium is a common reflective material in luminaires due to its good availability, weight and mirror-like reflectance. Generally, reflectance of aluminium increases with its purity. Chemically polished 99.99% pure aluminium can have a reflectance of up to 91.3%. [41] A mechanically polished 6061 aluminium surface, even though less pure, may have a reflectance of 95% [42]. However, reflections from aluminium are mostly specular [43]. This means the luminaire would require a diffusing film with a higher diffusivity to create a uniform luminance distribution on its surface. Thus polished aluminium will not be considered a possibility.

Labsphere Spectralon® is an extremely Lambertian reflective material with a reflectance of over 99%. It is often used in optical components. It is also environmentally stable and reasonably durable. [44] Spectralon® is, however, considered quite expensive and is also not studied further [45].

Barium sulfate ($BaSO_4$) is a common diffuse reflective coating with a reflectance of over 97%. It is commonly used in integrating spheres. [46] $BaSO_4$ is not durable and its reflectance degrades easily with contaminants. A potential solution is $BaSO_4$ mixed with white latex paint to produce good reflectance (up to 95% with 40% paint) while improving its durability. [45]

Dow Corning CI-2001 white reflective coating is also suggested as a possibility. This is a relatively expensive new product on the market, but was chosen due to its claimed high reflectance of up to 96% [47].

Reflective sheets are available ready-made from various manufacturers. These were chosen for comparison from Yongtek, A.L.P. Europe and Alanod.

Table 4: Reflective back plates for the luminaire.

Reflective back plate	Reflection	Reflectance [%]
Polished aluminium [42]	Specular	95
Labsphere Spectralon® Optical-grade [44]	Diffuse	>99
$BaSO_4$ [46]	Diffuse	>97
$BaSO_4$ mixed with 40% paint [45]	Diffuse	95
Dow Corning CI-2001 White reflective coating [47]	Diffuse	96
Yongtek White Reflective Sheet PET [48]	Diffuse	>96
A.L.P. Europe Brightview BrightWhite 98™ film [49]	Diffuse	>97.5
Alanod White98® Film F-16 [50]	Diffuse	>98

To further reduce losses, the back plate should be as close as possible to the LGP. This prevents light rays from scattering out to the sides. A suggested alternative is to apply a reflective paint on the backside of the LGP instead of having a separate reflective back plate. An added benefit of this is that the back plate can be placed immediately behind the LGP, removing the air gap completely, and thus the radiant properties of the panel are improved. This may prove problematic, since paint does not usually adhere well to PMMA and may compromise the function of the light scattering pattern. This is tested in chapter 3.

2.3.3 Diffusing Film

The diffusing film is a separate plate or film in front of the LGP. Its purpose is to even out the light distribution on the surface of the luminaire and diffuse the transmitted light. However, a plate on top of the luminaire also reduces the transmission of light, so the diffusing film is always a compromise between transmission and diffusion. [35] [36] This subchapter will show why a diffusing film is necessary and suggest and compare options for the diffusing film.

One cause of uneven distribution of light on the surface of the luminaire is a so-called hot-spot. A hot-spot is the area close to an LED which may seem brighter than its surrounding area. This is illustrated in Figure 11, where the yellow rectangles represent the light sources and the blue area the unevenly-lit LGP. Hot-spots become more obvious with a smaller number of LEDs. [7]

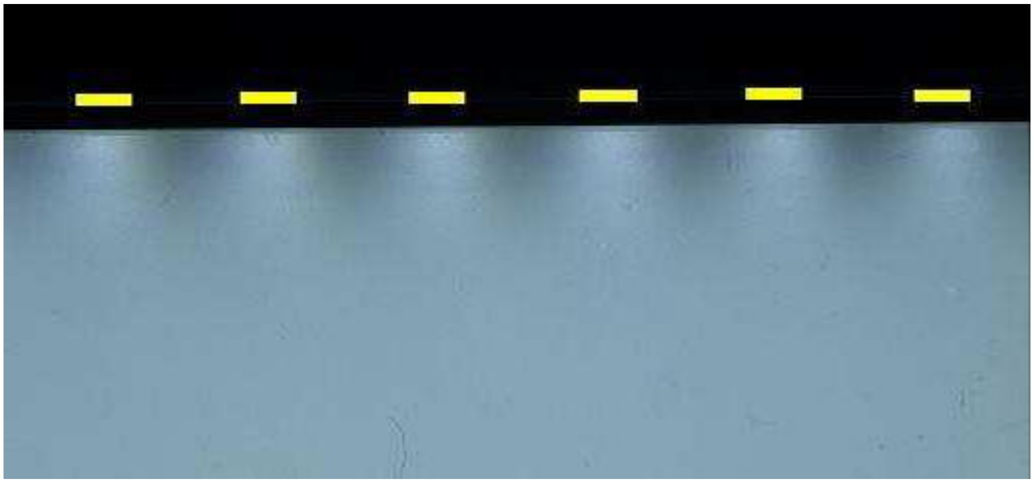

Figure 11: Illustration of the hot-spot phenomenon [7].

In this chapter, evaluation of the suggested diffusing films will be done based on how well they transmit light. Their effect on the distribution of light will be studied through measurement in chapter 3. The diffusing films are presented in Table 5 along with their transmittance and other relevant properties.

Table 5: Diffusing films for the luminaire.

Diffusing film	Material	Thickness [mm]	Transmittance [%]
Yongtek PA-75S2K Double Matte Diffuser [51]	PS	1.5	74
A.L.P. Europe Lumieo® DSE 80 [52]	PS	1.5	80
A.L.P. Europe Lumieo® Frost 80 [52]	PMMA	2	80
Alanod WhiteOptics® Micro-Structured Optics Film [53]	PET	0.127	>94
Alanod WhiteOptics® Glare Reduction Film [54]	PET	0.127	92 - 96
Alanod WhiteOptics™ Micro-Diffusion Film [55]	PET	0.127	93 - 95
Alanod WhiteOptics® DF-C [56]	PET	0.15	93 - 94
Sewon Precision diffuser plate [57]	PS	1.5	50 - 93

Based on the information in Table 5, the diffusing films offering the highest transmittance are those provided by Alanod and Sewon. The real value of the diffusing film is in its ability to even out the light distribution, so the films with lower transmittance may still prove to be the best choices here.

2.4 Visual Comfort and Aesthetics

Visual comfort in this thesis equates to the qualities of the luminaire which make the subject feel more comfortable with his or her surroundings and task. To represent the unpleasantness caused by lighting, the term *visual discomfort* is often used. Visual comfort here includes, but is not limited to, qualities eliminating those which cause visual discomfort. These may be too little or too much light, too much variation in luminous distribution, glare, reflections or flicker [58] [9] [59] [11].

Methods to avoid visual discomfort are outlined for luminaire design in the IESNA Lighting Handbook and the EN 12464-1 Light and Lighting standard [9] [3]. This subchapter will go through sources of visual discomfort and suggest ways to eliminate them. Ways to improve the aesthetic qualities of the luminaire will also be looked at, as these also play a part in providing visual comfort to the subject [9]. This thesis will only concentrate on a few of the main aspects of visual comfort, others have been left out, since they cannot be significantly altered.

2.4.1 Glare

Glare is the sensation of discomfort or reduction in vision produced by bright areas or extreme contrasts within the visual field [3] [4]. As mentioned in the introduction, this thesis will only study discomfort glare, which is quantified by the Unified Glare Rating (UGR). [9] [60] [59] [61] [12]

The Unified Glare Rating (UGR) system is a method by the International Commission on Illumination (CIE) to predict the amount of discomfort glare that is produced. Boyce, Hunter and Inclan have shown that UGR is a good representation of visual discomfort. [62] The formula used to calculate UGR is

$$UGR = 8\log_{10}\left(\frac{0.25\pi}{E_b}\right)(L^2 * \omega)/p^2, \tag{9}$$

where E_b is illuminance in the plane of the eye, excluding the glare source, L is the luminance of the glare source, ω is the solid angle of the glare source at the eye and p is the position index of the glare source [62] [60]. A UGR value of 10 equates to *imperceptible glare* and a value of 30 is *very uncomfortable glare* [62]. EN 12464-1 recommends a UGR value of less than 19 for regular office working conditions [3].

Equation 9 suggests that a big difference in glare source to background luminance results in a higher UGR value. Thus, bright spots on the luminaire could result in glare. These bright spots can be eliminated at the expense of total luminous flux by using a diffusing film that was suggested in chapter 2.3.3.

If the luminaire as a whole is thought of as the glare source, then glare is also possible if the area surrounding the luminaire is much darker than the luminaire itself. This could be minimized by guiding part of the emitted light towards the back of the luminaire if the luminaire is a pendant unit and not recessed into the ceiling. It has been shown that adding an intermediate luminance between the glare source and the background reduces the glare sensation [59]. Also, the IESNA handbook suggests that luminaire luminance should not be more than 100 times that of surrounding surfaces [9]. Another approach to solving this issue is to have adjustable brightness of the luminaire. This way the luminance can be adjusted to varying conditions. Implementing such a solution, however, is not within the scope of this thesis. Increasing the size of the luminaire can also help in reducing differences in luminances and thus also glare [12].

Equation 9 also suggests that UGR increases with the solid angle of the glare source at the eye and decreases greatly with the position index of the glare source. This means that if the luminaire is almost outside the field of view, UGR is minimized. So narrowing the luminous intensity distribution of the luminaire would increase visual comfort. This too can be achieved with the diffusing plate guiding light directly downwards instead of at a wide viewing angle. This might, however, increase the non-uniformity of illuminance, which has been shown to increase visual discomfort. [59]

2.4.2 Correlated Colour Temperature

CCT was already defined in chapter 2.2.1 and will not be studied too extensively here. Certain tasks require different CCTs [11], so to increase the visual comfort of the luminaire in different applications, it would be beneficial to have adjustable CCT. It has also been shown that certain CCTs change the mood of people, which affects visual comfort [59] [13]. This, however, is not within the scope of this thesis and is merely suggested as a possible future improvement for this luminaire.

2.4.3 Aesthetic Qualities

Patterns of light and shadows may affect task visibility, comfort and perceptions [9]. Excessive bright spots and noticeable shadows should be avoided to minimize visual discomfort, but also to change the way the luminaire looks. This can be done by eliminating bright spots on the surface of the luminaire as already suggested before.

The luminaire also needs to be white in appearance when turned off, as per the requirements of chapter 1.2. This means the back plate needs to be white, since the LGP and diffusing plates are fully or nearly transparent.

Another aesthetically significant property is the colour rendering of the luminaire. This is the effect of an illuminant on the colour appearance of objects by comparison with their colour appearance under a reference illuminant. This is quantified with the colour rendering index (CRI), which is a measure of how well the colour appearance of objects under the illuminant compares to that under the reference illuminant, suitable allowance having been made for the state of chromatic adaptation. [4] The CRI is usually measured with the R_a value, which has a maximum value of 100. [9] [11] [12] This means that with a higher R_a value, the illuminated area should feel visually more comfortable and appear aesthetically more pleasing than with a lower R_a value. The EN 12464-1 standard and the IESNA lighting handbook recommend that R_a in regular office working conditions should be over 80 [3] [9]. To ensure this criterion is met, the light sources chosen for the luminaire have $R_a > 80$.

Shadows are known sometimes to cause visual discomfort, but are also a design tool for creating the visual environment. Stronger shadows, which cause discomfort, are produced by single point sources and weak shadows, which increase visual comfort, are produced by larger sources. [59] Thus a larger luminaire, like the one being developed, is beneficial for visual comfort.

3 Development of the Luminaire

This chapter describes the development process of the luminaire and how the measurements done help in improving the luminous efficacy and visual comfort. The first part describes the measurement setup and methods used in the measurements, the next explains what measurements and improvements were made to better the luminous efficacy of the luminaire, and the last part explains how the visual comfort was improved.

3.1 Measurement Setup and Methods

The measurement setup includes an integrating sphere, goniophotometer and a luminance mapping camera. These are used as the main tools for creating repeatable data of the luminaire. Just as important as the equipment, are the methods used in measuring and setting up the equipment. Care is taken to ensure every step of the measurements are repeatable. Installing the components to the test luminaire is done carefully and systematically, as positioning of the components may have a significant influence on the light transmitted [36]. All measurements are done at a laboratory at Aalto University.

3.1.1 Integrating Sphere

The integrating sphere with a spectroradiometer is a tool for measuring total radiant flux Φ_e of light sources. Luminous flux Φ_V and colour quantities can be calculated from this. The inside of the sphere is coated with a material such as $BaSO_4$ which has high and diffuse reflectance, usually 90-98 %. [9] [63] This reflects and diffuses light so that the illuminance distribution is uniform [64].

The integrating sphere used is manufactured by *Labsphere* and has a diameter of 2 meters. It has a 4π geometry, as recommended for SSL measurements by the Illuminating Engineering Society (IES) [63]. The spectroradiometer is a *Labsphere DAS-2100* with an optical fibre input. This equipment is shown in Figure 12. To measure the input power P of the luminaire, a *Yokogawa WT130* digital power meter is used. The supply voltage V is set to 230 V. To measure the input current of the LED modules a *Fluke i30* current clamp connected to a *Fluke 73* digital multimeter is used.

Luminous flux Φ_V is the primary quantity, which this thesis is interested in. Dividing Φ_V with P yields the luminous efficacy η [9]. The colour quantities of interest are the CRI and CCT. These are calculated automatically with the software on the computer, which is connected to the serial output of the spectroradiometer.

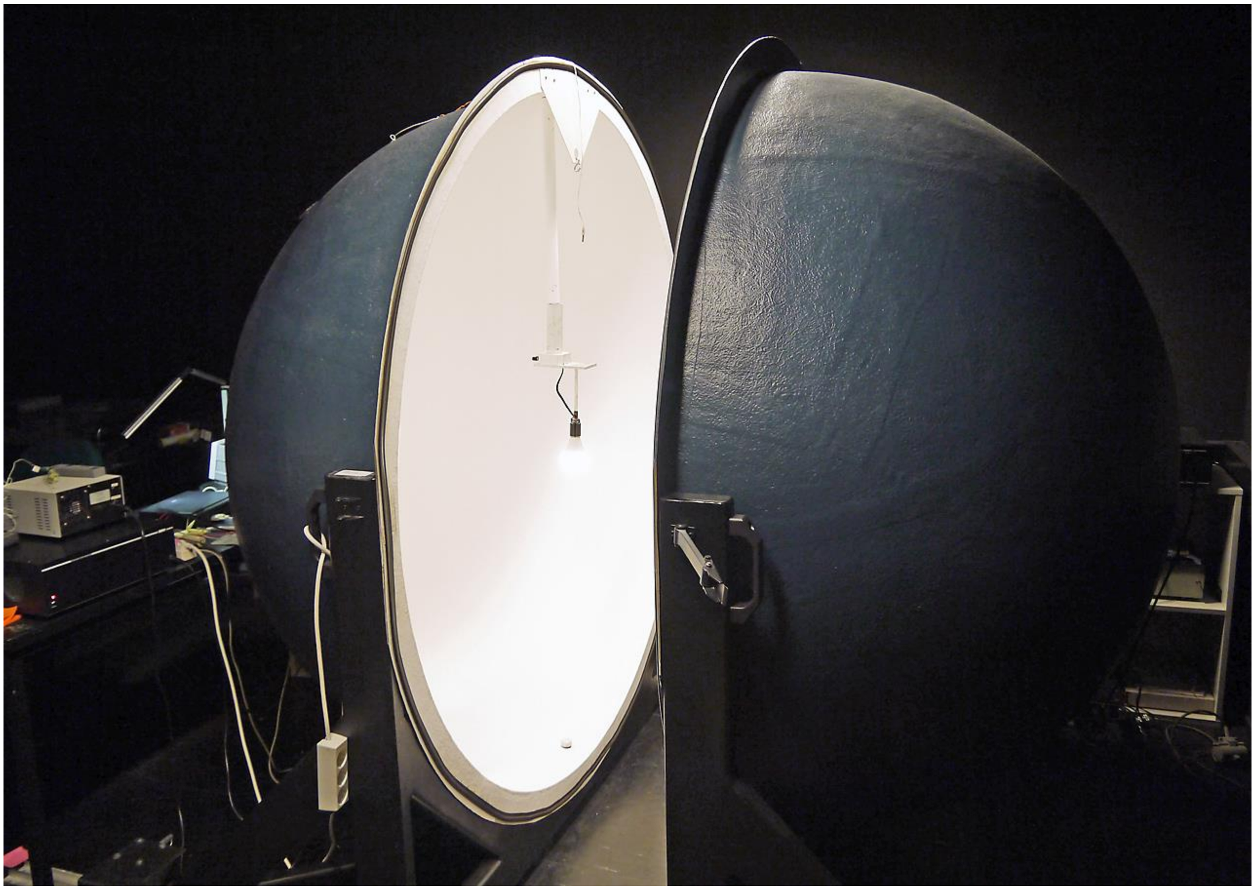

Figure 12: Labsphere integrating sphere with Labsphere DAS-2100 spectroradiometer. [64]

Ambient conditions are controlled during the measurements to ensure consistency of results. Heat can be a problem when measuring SSL products, as it may accumulate inside the sphere and change the operating conditions of the luminaire. The temperature T_a inside the sphere should be kept at 25 ± 1 °C. [63] This is controlled with air-conditioning in the laboratory.

As per recommendations, the luminaire is allowed to reach operating temperature before the measurements. The measurement equipment is also allowed a 30-minute warm-up time. The light-absorption of the luminaire is compensated for with auxiliary lamp correction. [63]

3.1.2 Goniophotometer

The goniophotometer is a tool for measuring luminous intensity distribution [9] [63]. The photometer or the light source moves with respect to the other in a spherical plane. The photometric data is then exported into a EULUMDAT file. [64] The IES recommendation for scanning resolution is C = 22.5 degrees and γ = 5 degrees for this type of smooth intensity distribution [63]. The measurements in this thesis are done with a resolution of C = 15 degrees and γ = 5 degrees.

The equipment operates in an open space, so is not subject to heat accumulation as with the integrating sphere. The photometer head needs to reside at a distance of at least 5 times the largest dimension of the luminaire. This ensures that the light source can be treated as a point-source and the measurement calculations are valid. [63] [46] In this case, the luminaire is a rectangle of 1.2 m * 0.6 m, so the largest dimension is approximately 1.34 m. Thus the minimum distance for the photometer is approximately 6.7

m. The goniophotometer is allowed to reach operating temperature before the measurements as is the luminaire. Both are given a one hour stabilization time.

The goniophotometer used here is an OxyTech T2. It is a mirrorless meter, where the light source moves while the photometer head remains stationary. The setup is shown in Figure 13.

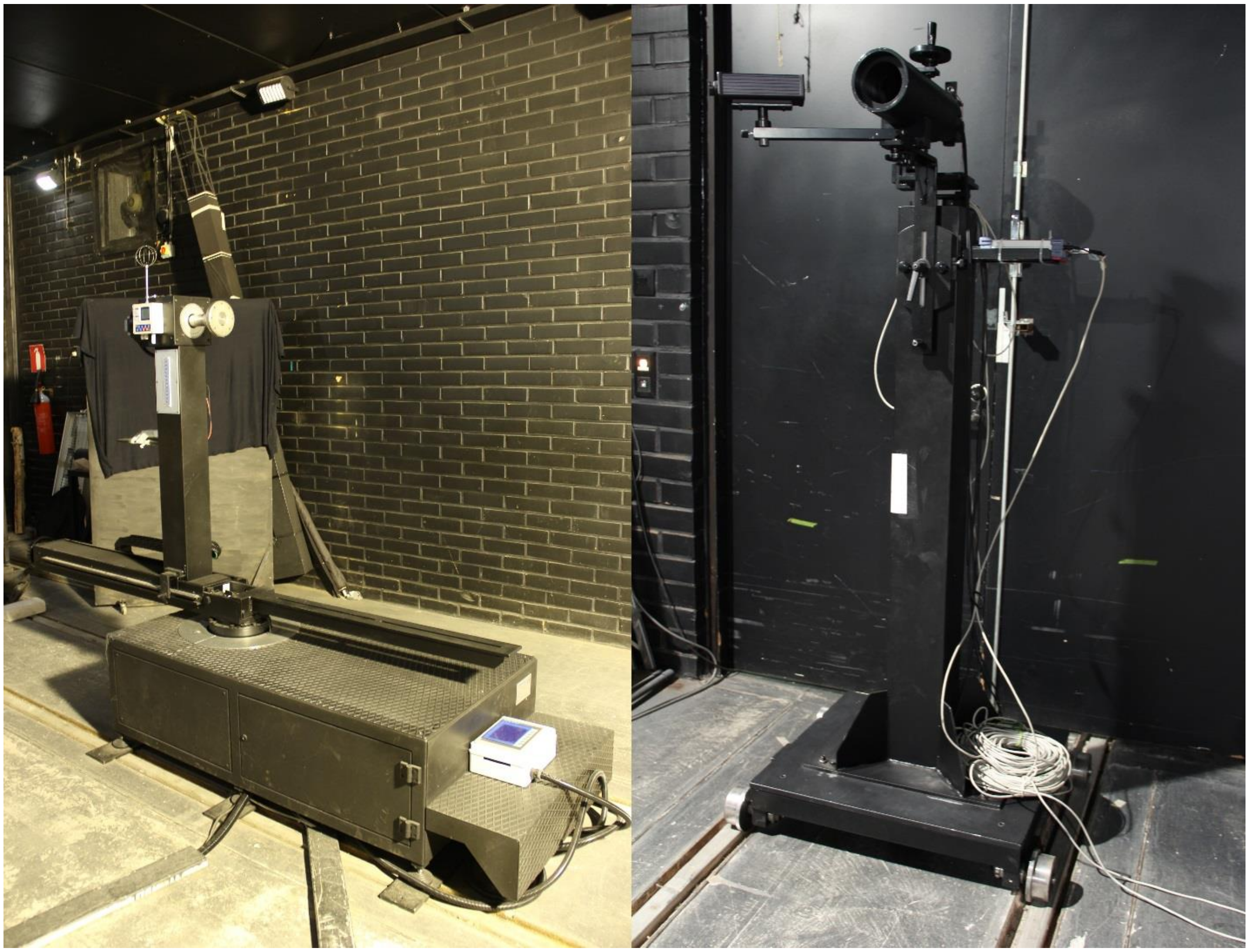

Figure 13: OxyTech T2 goniophotometer at Aalto University. The luminaire mounting system is on the left and the photometer head on the right.

3.1.3 Luminance Mapping Camera

The luminance distribution on the surface of the luminaire is measured with an LMK luminance mapping camera. A calibrated camera takes a series of images of the luminaire, which are then opened with a program to show the luminance distribution.

The camera used is a Canon EOS 350D and the software is LMK Laboratory Software 10.8.20. To ensure stability of consecutive images, all measurements are done on a tripod. The equipment is shown in Figure 14.

Figure 14: Canon EOS 350D Luminance mapping camera measurement setup.

3.2 Improving Luminous Efficacy

This subchapter will find those components which work best to improve the luminous efficacy of the luminaire. The components are measured and the results are compared to the theory which was studied in chapter 2. The first part compares the chosen new LED modules with the old ones. In the subsequent parts the optical components are changed one by one in the complete luminaire and a conclusion is drawn as to which works best for each part. The old LED modules will be used in those measurements as the light source.

3.2.1 Light Source

The light sources that were preinstalled in the luminaire are LED packages (Citizen Electronics, Citiled CLL130-0101B2, Japan) mounted in four LED modules. The new LED packages (Osram Opto Semiconductors, DURIS S2, Germany) are also integrated into modules, but only one module was tested. These modules were tested without the luminaire to eliminate absorption of light to it and shadowing from it. LEDs, however, use the luminaire as a heat sink, so their warm-up time was limited to 10 minutes to avoid overheating. The results of the measurements are shown in Table 6.

Table 6: Light source measurements.

LED module	Citizen Citiled CLL130-0101B2	Osram DURIS S2
Supply voltage V [V]	230.0	230.0
Power P [W]	61.1	42.2
Temperature T_a [°C]	24.9	24.9
LED forward current I_F [mA]	40.7	55
Luminous flux Φ_V [lm]	6323	4909
Measured luminous efficacy η [lm/W]	103.5	116.3

T_a here is the ambient temperature inside the sphere during measurement. The total current to the LED module was measured and then divided by the number of LEDs in parallel to get I_F. The results should be compared to the effective luminous efficacy η_{eff}, which is calculated with the coefficients from Table 2 on page 12. The effective luminous efficacies are 115.2 lm/W and 154.7 lm/W for the Citizen and Osram packages, respectively. Note that η_{eff} here does not include the optical loss coefficient $K_{\eta O}$, since the measurements are made without the LGP. The effective luminous efficacies could be even lower, since the modules do not have the luminaire as a heatsink and thus the coefficients for thermal efficiency $K_{\eta T}$ could be lower.

Another reason why these results are lower than expected is because the measured input power includes the inefficiency of the LED driver as well. At these loads, the drivers for the Citizen and Osram LEDs have efficiencies of 94% and 85.4%, respectively [65] [66]. Also, around 1.7 W of parasitic power is measured to be consumed by the dimming module, which is used to control the driver during measurements. Subtracting the parasitic power of the dimming module from the total power consumed and considering the driver inefficiencies as coefficients, the measured luminous efficacies are close to the calculated theoretical ones at 113.2 lm/W and 141.9 lm/W, respectively.

The effect of the forward current on the luminous efficacy was neglected in chapter 2.2, since it was assumed that the recommended forward current be used. However, the forward currents from the LED drivers are not the recommended ones. Both LED drivers employ a lower I_F than recommended, so the luminous efficacies should be higher, as discussed in chapter 2.2. The effect is minimal in any case.

3.2.2 Light Guide Plate

The LGPs were tested by measuring the luminous output of the luminaire. All other components were kept the same from one measurement to the next. The back plate used was the Yongtek. Reflective aluminium tape was used to seal the non-illuminated edges of the LGPs, as suggested in chapter 2.3.1, so that as much of the light as possible was directed out of the luminaire. This is shown in Figure 15.

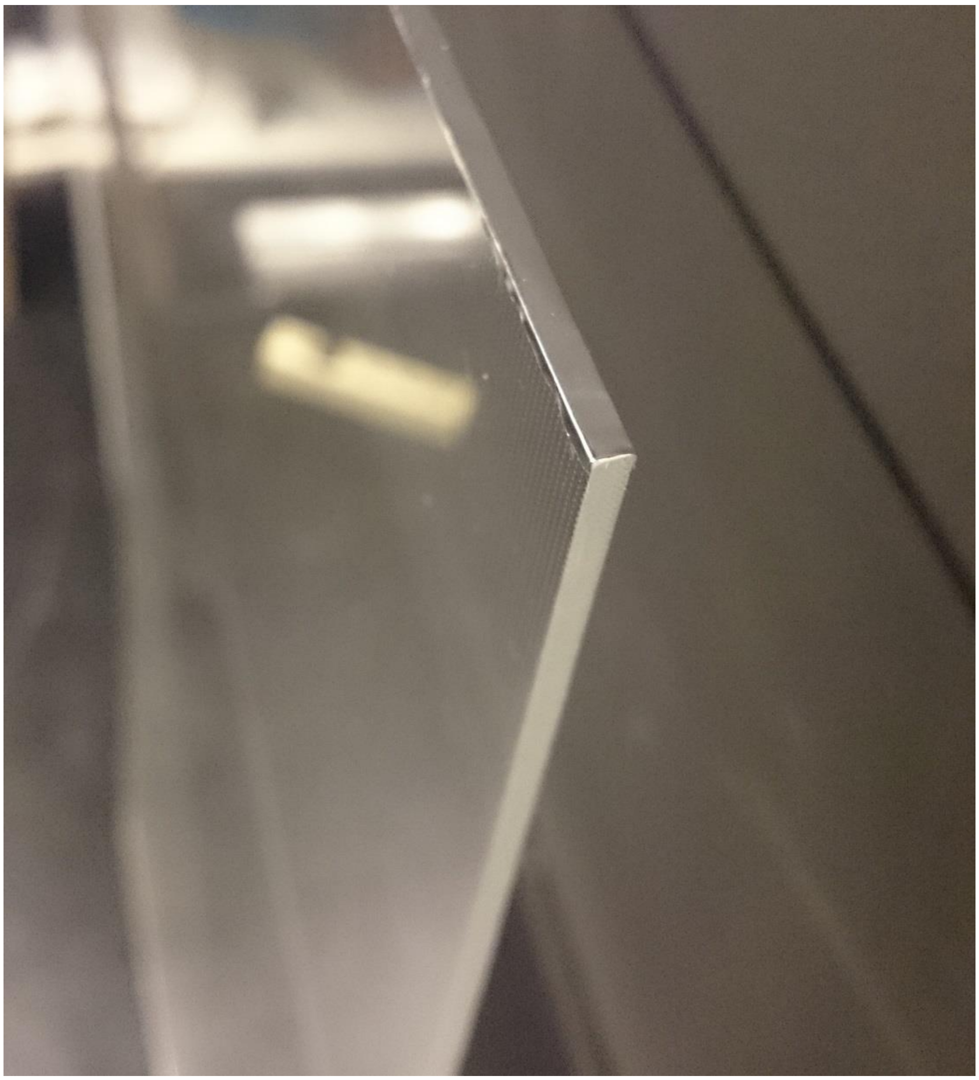

Figure 15: Aluminium tape used to optimize transmission of light in the preferred direction.

The tested LGPs are 3 mm thick, so they had to be tested with the diffusing film in place to align the edge of the LGP with the LEDs. Knowing the transmittance of the diffusing film, and assuming the stated value is correct, we can calculate the luminous efficacy of the luminaire without it. The diffusing film used here is the Yongtek with a transmittance of 74%. Similar results were attained with the A.L.P. diffuser. The results of the measurements and the calculated luminous efficacies without the diffusing film η_{calc} can be seen in Table 7.

Table 7: Luminous efficacy of the luminaire with different LGPs.

LGP	Measured luminous efficacy of luminaire, η [lm/W]	Calculated luminous efficacy of the luminaire without the diffusing film, η_{calc} [lm/W]
Caverion prototype LGP	77.0	-
Yongtek LGP	62.5	84.5
A.L.P. Europe LGP	55.9	75.5

Alignment of the LGPs with the LEDs was found to be very difficult and a 3mm LGP cannot be recommended without altering the LED position on the PCB or the luminaire design. A significant quantity of light escapes past the edge of the thinner LGPs.

The A.L.P. LGP had a protective film only on one side on arrival, and the other side was noticeably damaged due to the sub-optimal packaging. Figure 16 shows that the scratches are visible with the LEDs turned on. This was expected to have an effect on the luminous efficacy, since the scratches do have an effect on the opacity of the LGP. The results show that the A.L.P. LGP falls behind both the Yongtek and the Caverion LGPs in luminous efficacy.

Figure 16: Scratches on A.L.P. LGP due to poor packaging.

3.2.3 Reflective Back Plate

The reflective back plates were tested in a similar fashion to the LGPs: The reflective back plate was changed and the luminous output of the luminaire was measured. All other components were kept the same to eliminate any other factors affecting the measurement results. The LGP used in the measurements was the Caverion prototype LGP preinstalled in the prototype luminaire and no diffusing film was attached. Again, aluminium tape was used to seal the edges of the components so that as much of the light as possible was directed towards the LGP.

The Dow Corning CI-2001 White Reflective Coating was painted onto the back plate, which was preinstalled in the luminaire. All other measurements requiring that back plate were thus made before this. After all measurements, the back side of the Caverion prototype LGP was painted with this coating and measured. The results can be seen in Table 8.

Table 8: Luminous efficacy of the luminaire with different reflective back plates.

Reflective back plate	Luminous efficacy of luminaire η [lm/W]
No back plate	68.1
Yongtek back plate	77.0
A.L.P. Europe back plate	77.4
Dow Corning CI-2001 White Reflective Coating on back plate	74.7
Dow Corning CI-2001 White Reflective Coating on back side of Caverion LGP	68.5

The results show that the luminous efficacy increases with the reflectance of the back plate. The A.L.P. Europe back plate offers the greatest luminous efficacy, so this is recommended. In the final experiment, the Dow Corning CI-2001 White Reflective Coating did adhere to the LGP, but compromised the function of the scattering pattern, as was expected. The luminance distribution was very uneven, and this solution cannot thus be recommended.

3.2.4 Diffusing film

The diffusing films were tested in a similar fashion to the LGPs and the reflective back plates. The luminous output of the luminaire was measured with each of the diffusing films while all other components were kept the same. To allow for the thickness of the diffusing films, a thinner LGP was used - the Yongtek in this case. The Yongtek reflective back plate was also used.

It is difficult to measure the luminous efficacy of the 3 mm LGP without the diffuser, since a significant quantity of light escapes past the LGP and provides inaccurate results. The diffusing films are thus compared to one another. The results can be seen in Table 9.

Table 9: Luminous efficacy of the luminaire with different diffusing films.

Diffusing film	Luminous efficacy of the luminaire, η [lm/W]
Yongtek PA-75S2K	62.5
A.L.P. Europe Lumieo® Frost 80	64.2

Dividing by the diffusing films' claimed transmittances results in luminous efficacies of 84.5 lm/W and 80.3 lm/W for the Yongtek and A.L.P, respectively. These values should be similar to one another if the claimed transmittances are to be trusted. The error might also be due to the 0.5mm difference in thickness of the diffusing films, which may cause misalignment of the LGP and distort the results. A similar difference was attained using the A.L.P. LGP.

3.2.5 Summary

The chosen tested components show percentual increases as presented in Table 10. These can be used to conclude that these components could increase the luminous efficacy of the luminaire up to 95.7 lm/W in total. The effect of the diffusing film is not included in this value, since it has a negative effect on the luminous efficacy of the luminaire.

Table 10: Summary of components improving luminous efficacy.

Component	Component chosen	Luminous efficacy with original component, η [lm/W]	Luminous efficacy with new component, η_2 [lm/W]	Percentual difference in luminous efficacy [%]
Light source	OSRAM DURIS S2	103.5	116.3	+12.3
LGP	Yongtek	77.0	84.5	+9.7
Reflective back plate	A.L.P. Europe Lumieo® Frost 80	68.1	77.4	+13.7

Areas that can still be improved on are the LEDs. The light source made such a big difference on the luminous efficacy that LEDs with a narrower beam angle and higher luminous efficacy should be considered as suggested in chapter 2.2.4.

3.3 Improving Visual Comfort

The second part of the measurements focuses on improving visual comfort. This subchapter will go through the different components of the luminaire which have been changed and determine whether the modifications have been successful from the point of view of visual comfort.

3.3.1 Light Source

The effect the light source has on the visual comfort is limited to its CRI and CCT. The modules compared here are the same as in chapter 3.2.1. These were measured by themselves and the results are presented below in Table 11. The CRI and CCT meet the requirements. Other conclusions with regards to visual comfort cannot be made, since these are just the LED modules by themselves.

Table 11: Light source measurements.

LED module	Citizen Citiled CLL 130-0101B2	Osram DURIS S2
CRI, R_a	84.7	91.2
CCT, T_{cp} [K]	4313	4017

3.3.2 Optical Components

Various combinations of the available components were measured with the luminance mapping camera and inspected visually to determine whether there is any hotspot phenomenon and if the luminance distribution is uniform. The combinations to be studied all have the Citizen LEDs (Citizen Electronics, Citiled CLL130-0101B2, Japan) and the A.L.P. reflective back plate.

The luminance mapping images for the various combinations are presented in Figure 17 on the following page. The images are scaled to the same luminance values, so that the luminance distributions are comparable. 100% signifies the maximum luminance. The first combination has the Yongtek LGP with the Yongtek diffusing film. The second combination has the Yongtek LGP with the A.L.P. diffusing film and the last combination has the Caverion LGP with no diffusing film.

The luminance is much higher towards the edges when using the diffusing film. A possible cause for this could be the misalignment of the LEDs with the LGP, which causes light to escape between the LGP and the diffusing film. This is supported by the fact that this phenomenon is not as clearly present when the diffusing film is not in place. This could be prevented with a wider luminaire frame that would cover more of the luminaire surface. This however, would reduce the illuminating surface area of the luminaire and possibly lower its luminous efficacy.

The LED modules are split at the centre of the luminaire, which presents as the hotspot phenomenon. This is also apparent towards the corners where there are no LEDs. The OSRAM LED modules have a more uniform distribution of LEDs, and should solve this problem.

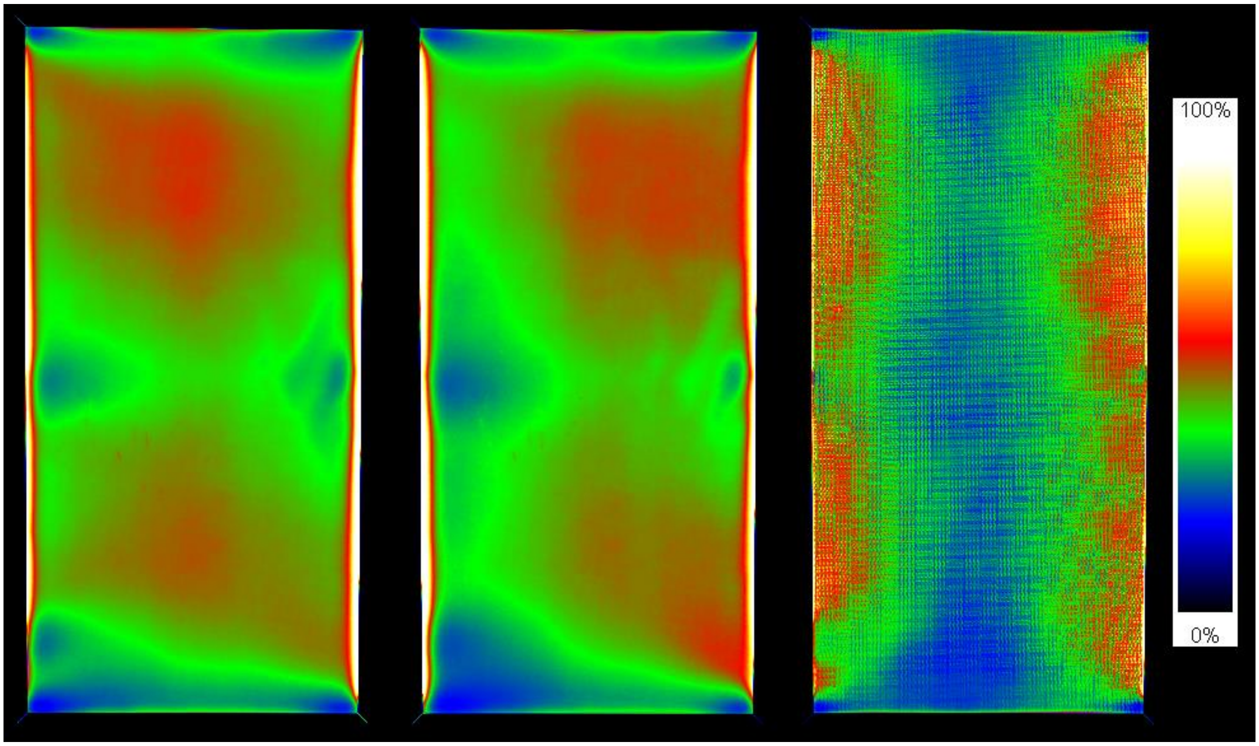

Figure 17: Relative luminance mapping images of the luminaire with different combinations of optical components.

In the absence of the diffusing film, the scattering pattern of the LGP is visible in the luminance mapping image. This, however, is not visible to the naked eye, so is not considered a problem and thus the diffusing film is seen as unnecessary for a uniform luminance distribution. The Yongtek LGP seems to distribute the light more evenly across the surface than the Caverion LGP. This is visible both in the luminance mapping image and with the naked eye.

The difference between the minimum and maximum luminances was calculated across the width of the luminaire. This was done at a height one fourth from the top of the luminance mapping image. The extreme luminances at the edges were neglected. The difference between the highest and lowest luminances with the Caverion LGP was 52%, while with the Yongtek LGP with the A.L.P. and Yongtek diffusing films it was 12% and 14%, respectively. Since the observed width is wide, the effect of the diffusing film on the difference in luminances can be neglected. This shows that the Yongtek LGP distributes the light more uniformly across the surface of the luminaire, as was suspected.

3.3.3 Summary

The CRI is improved with the OSRAM light source. However, the CRIs of both light sources exceed the requirements. The CCT is lower with the OSRAM, but still above the required value. Thus no additional visual comfort is achieved by changing the light source.

Bright spots are clearly visible in all combinations of the optical components, especially close to the LEDs when using a thinner LGP. The luminance distribution is however more uniform with the improved LGPs and the Yongtek LGP is thus recommended. This means that the luminaire needs to be redesigned for a thinner LGP to avoid the hotspot phenomenon caused by light escaping between the LGP and the diffusing film. Altering the distribution of the LED packages on the LED modules would also reduce the bright spots, since the darker areas in the centre and towards the edges of the luminaire would be removed. Based on this evaluation, a diffusing film is not considered necessary when observing the luminance distribution.

4 Evaluation of the Luminaire

In this chapter the developed luminaire is evaluated with simulations done with DIALux. UGR and illuminance will be calculated and compared to the requirements set by the EN 12464-1:2011 Light and lighting standard in regular office conditions.

4.1 Simulation

DIALux 4.11 software is used to run a simulation on the light distribution of the luminaire in two types of office rooms. This is done based on the luminaire data measured with the goniophotometer. The luminous intensity distribution of the luminaire doesn’t change with luminous flux, so the same goniometer measurement data can be modified to account for different levels of dimming simply by changing the luminous flux and the power. The luminous flux and power used for the measurements are based on data from Caverion’s next generation luminaire, which is based on the luminaire being developed and the discoveries made in this thesis. When dimmed to 40% power, the luminous flux is 5982 lm and power is 54.0 W.

The luminous intensity distribution for the luminaire is shown in Figure 18. The distribution is very even, so the luminaires are expected to give a uniform distribution of light in the simulations.

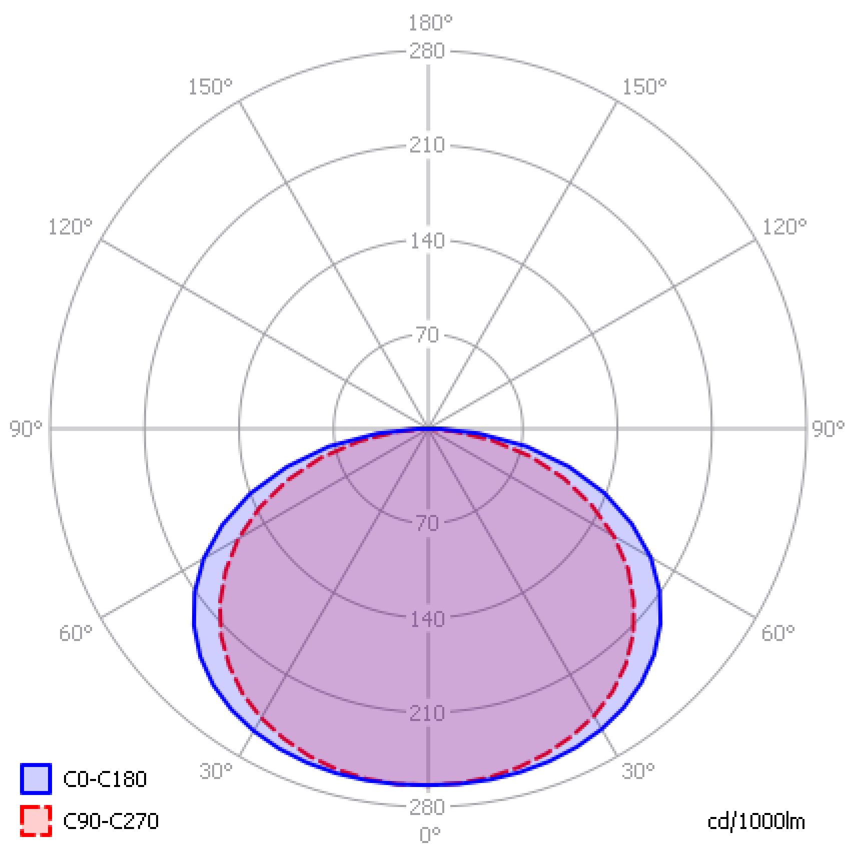

Figure 18: Luminous intensity distribution for the luminaire.

The objective of this simulation is to see if the illuminance requirements in an office room can be fulfilled with a minimal quantity of luminaires and how much glare the luminaires produce. The results are compared to the requirements set by the EN 12464-1:2011: Light and lighting standard.

The simulations are run in two different environments. The first is a private office room and the second environment is an office room for four employees. The simulations are run with 2 luminaires per person mounted in the rooms, since this represents the construction of the final product. The materials chosen for the ceiling, walls and floor are colour 9010 (Pure White), colour 9002 (Grey White) and standard floor, respectively. The properties of the rooms are presented in Table 12.

Table 12: Simulation environment properties.

	Office 1	Office 2
Length [m]	4.1	10.5
Width [m]	2.6	5.1
Height [m]	2.6	2.6
Ceiling reflectance [%]	86	86
Wall reflectance [%]	68	68
Floor reflectance [%]	20	20
Number of luminaires	2	8

UGR varies with viewing angle, so to simulate regular working conditions, the viewing direction is aimed at the computer on each desk, where applicable. The height of the UGR measuring point is that of eye-level depending on the location. While sitting down in an office chair, eye-level is assumed to be 1300 mm from ground-level. At a regular chair this is assumed to be 1200 mm.

To measure the illuminance at task areas, illuminance calculation surfaces are added to suitable locations. These are at office desks and the table and printer in Office 2. The height of the calculation surface is 800 mm from ground-level.

The offices are furnished with usual office equipment. The material choices for the office equipment are those of a typical office. The floor plans and 3D representations of Offices 1 and 2 are presented in Figures 19 and 20, respectively.

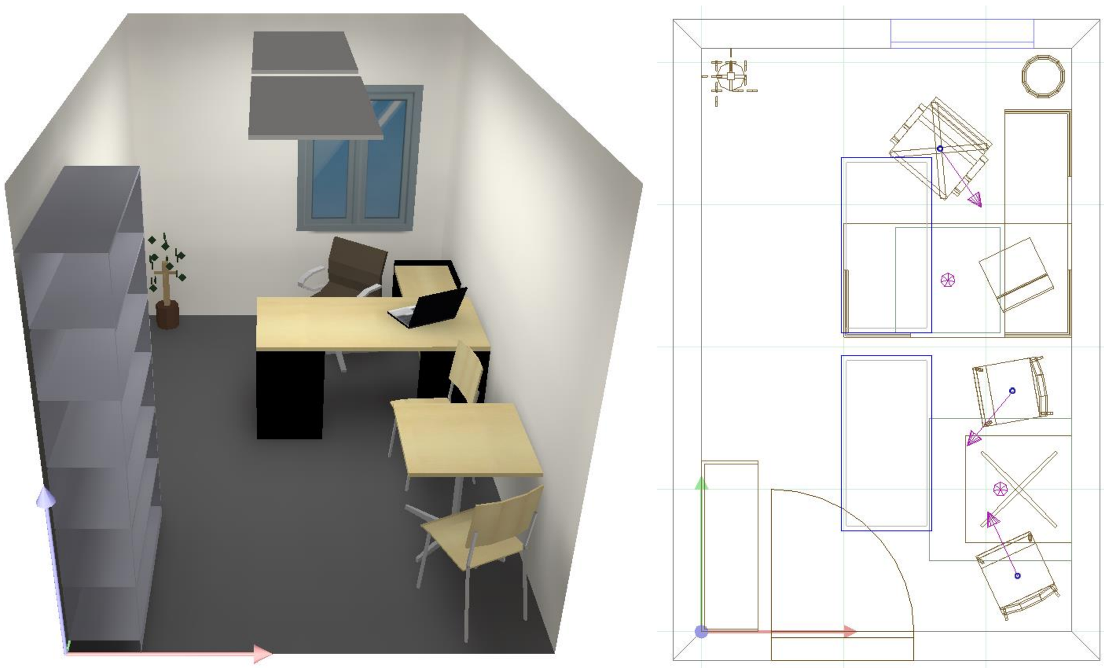

Figure 19: 3D view and layout of simulated Office 1.

Figure 20: 3D view and layout of simulated Office 2.

4.2 Results

To evaluate the performance of the luminaires in these settings, the illuminance and glare levels at the calculation surfaces and UGR calculation points are compared to the requirements set by the EN 12464-1:2011 standard. The results for illuminance and UGR are presented in Tables 13 and 14, respectively. The quantities of interest are the maintained illuminance E_m on the calculated surfaces, the illuminance uniformity U_0 on the same surfaces and the UGR values at the UGR measuring points. A complete set of simulation results can be found in the appendix.

Table 13: Simulation results for illuminance.

Calculation surface	Maintained illuminance E_m [lx]	Illuminance uniformity U_0
Office 1, desk	916	0.890
Office 1, table	730	0.781
Office 2, desk 1	884	0.608
Office 2, desk 2	867	0.667
Office 2, desk 3	933	0.603
Office 2, desk 4	945	0.768
Office 2, table	398	0.807
Office 2, printer	383	0.921

Table 14: Simulation results for UGR.

UGR calculation point	UGR
Office 1, desk	13
Office 1, chair 1	18
Office 1, chair 2	12
Office 2, desk 1	17
Office 2, desk 2	16
Office 2, desk 3	17
Office 2, desk 4	15

As mentioned earlier, the minimum maintained illuminance in offices for writing, typing, reading and data processing is 500 lx and for filing, copying, etc. is 300 lx with minimum illuminance uniformities of 0.60 and 0.40, respectively. The maximum UGR limit for typical office activity is 19. [3] These requirements are fulfilled with these luminaires at 40% power.

5 Discussion

The luminous efficacies of another 3 similar LED luminaires of different sizes were measured for comparison. Luminaires A and B have claimed luminous efficacies of greater than 80 lm/W, and luminaire C of greater than 100 lm/W. All luminaires have a diffusing film in front of the luminaire. The luminaires were measured first as they were built and then with everything removed apart from the LED modules. This way the losses in the optical components can be observed. The results are presented below in Table 15.

Table 15: Luminous efficacies of luminaires A, B and C.

Luminaire	η as built [lm/W]	η LED modules [lm/W]	Efficacy lost in optics [%]
A (600mm x 600mm)	85.1	91.9	7.4
B (300mm x 1200mm)	83.1	94.6	12.2
C (600mm x 600mm)	102.5	133.3	23.1

Luminaires A and B are from the same manufacturer and have similar constructions, the same LEDs and the same LED driver. Luminaire B, however, has a greater drop in luminous efficacy in the optical components. This is likely due to the fact that the LEDs are only located on one of the longer edges, instead of both. This makes the distribution of light more challenging as the opposite edge of the LGP needs to have a high reflectance. Luminaires A and B employ a white adhesive film on the backside of the LGP as a reflective back plate. This may improve luminous efficacy by eliminating the airgap between the LGP and the back plate and preventing any light escaping to the sides.

Luminaire C shows a greater decrease in luminous efficacy when assembled than luminaire A, even though they are of similar size. This is probably due to it having a thicker diffusing film, which usually corresponds to a lower transmittance [36]. Its necessity is questionable, since the results of this thesis showed that the diffusing film is not necessary for a uniform luminance distribution. The luminaires also appear visually very similar to one another. Luminaire C also has LED modules on all four edges of the LGP. Possibly some of the emitted light is absorbed in the LED module on the opposite side, instead of being reflected back to the LGP.

Many of the components suggested in the theory section of this thesis were not available for testing. This was mainly due to the time constraints of this thesis and partly due to the less than favourable response time of the manufacturers. The said components look promising and would still offer interesting subjects for research and possibly even better luminous efficacy or visual comfort.

Further ideas for development of this luminaire include redesigning the aluminium profile where the LEDs are located, as this seems to let some of the light escape; changing the LED packages to more suitable ones with a narrower beam angle and a higher luminous efficacy; and adding some kind of lens between the LEDs and the LGP to improve transmission of light. The last idea could also be implemented by profiling the edge of the LGP.

To further improve the luminous efficacy of the LED modules, thermal paste should be used to mount the modules to the luminaire. This way the heat generated by the LEDs would be transferred away more efficiently and the junction temperature would reduce. The benefit of lowering the junction temperature was shown in chapter 2.2.2. Another possibility could be to use thermal tape, which would make assembly easier than with thermal paste. Also a better conducting PCB for the LED modules should be used.

The reflective back plate was shown to have a significant impact on the luminous efficacy of the luminaire. The reflective coating by Dow Corning showed an improvement over the original painted back plate. However, the cost of the reflective coating was quite high and requires additional effort in painting and thus this cannot be recommended if the final product is to be mass-produced.

The simulations showed that these luminaires can produce enough light to illuminate office rooms without causing more discomfort glare than what is allowed. The simulations were run at 40% power, which means that as the LEDs degrade with time, the same level of illuminance can be maintained by increasing the power of the luminaires. This lengthens the rated life of the luminaires, which is defined partly by the degradation of the LEDs [17].

6 Conclusion

The increasing popularity of LEDs in luminaires has been shown to be justified. Further improving luminaires by integrating other building automation systems to them is an interesting concept put forward in this luminaire by Caverion. The luminous efficacy and visual comfort of the luminaire were improved significantly in this thesis. This thesis shows that it is possible to reach around 100 lm/W and limit the amount of glare to within tolerances.

The solution provided here is a thin LED luminaire working on a principle similar to the back light units in LCDs. The concept is simple, but attention must be paid to the LED packages and the reflective back plate, since these have the most significant effect on the luminous efficacy of the luminaire. Further improvements were made with the prototype luminaire by using reflective aluminium tape in sealing component edges and in mounting the optical components to the luminaire. This way less light could escape to the inside of the luminaire but rather be directed towards the LGP.

It was shown that 95.7 lm/W can be reached with this luminaire and this was achieved with the next generation prototype luminaire produced by Caverion. This will also be further increased when the HVAC part becomes active, since it effectively adds water-cooling to the LEDs. This was shown to improve the luminous efficacy significantly.

The other aspect of the luminaire which was improved is the visual comfort. This was improved using a different LGP, which provided a more uniform luminance distribution on the surface of the luminaire. The glare produced by the luminaire was evaluated with simulations. This was found to be within tolerances set by the EU standard EN 12464-1. Also the recommended illuminance was reached with a favourable positioning of the luminaires in simulated office rooms.

All the above requirements were met at 40% power. The luminous output of LEDs degrades with time, so the power can then be increased, lengthening the rated life of the luminaire and reducing maintenance or replacement costs.

Further improvements to the luminaire can be achieved by changing the LED packages to ones with an even higher luminous efficacy and by optimizing their thermal performance. This can be achieved by using thermal paste or tape to conduct heat away from the LED more efficiently. Also redesigning the aluminium profile would help improve the luminous efficacy, since this would allow for better thermal contact, and reduce the amount of light transmitted in unwanted directions.

Suggestions related to this luminaire to be researched in the future could include implementing adjustable CCT for further visual comfort and a lens between the LEDs and the LGP, maximizing the amount of light transmitted into the LGP. Profiling the edge of the LGP might achieve something similar to this. Utilizing organic light-emitting diodes (OLEDs) for this type of luminaire might also be an interesting solution. This might overcome some of the issues studied here as the OLED lighting panel could replace the LGP altogether.

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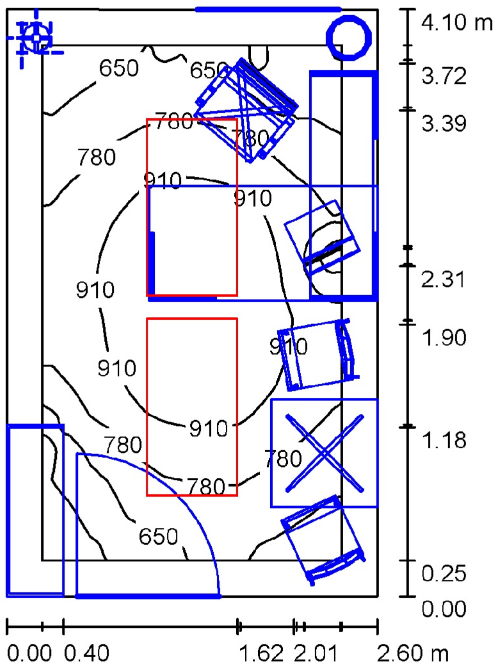
Office 1 / Summary



Height of Room: 2.600 m, Mounting Height: 2.600 m, Maintenance factor: 1.00

Values in Lux, Scale 1:53

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	796	426	1040	0.535
Floor	20	322	24	579	0.075
Ceiling	86	201	41	278	0.202
Walls (4)	68	363	4.93	802	/

Workplane:

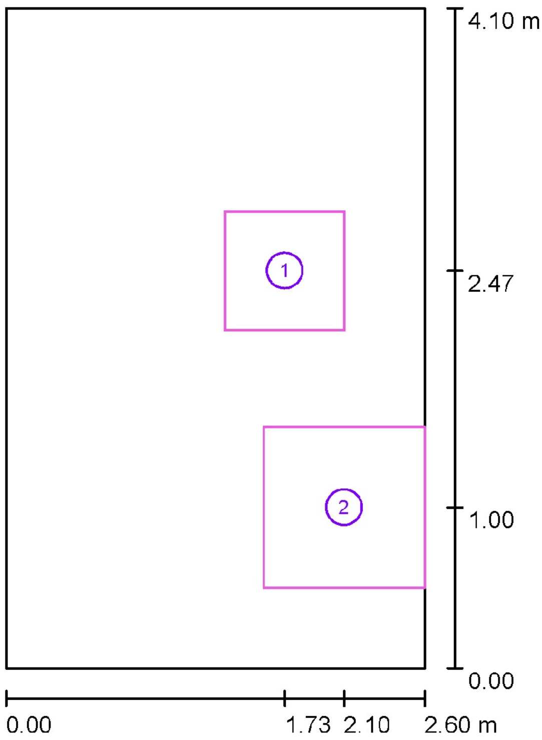
Height:	0.850 m
Grid:	128 x 128 Points
Boundary Zone:	0.250 m

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	2	Caverion, DurisS2,6k Caverion, DurisS2,6k Caverion, DurisS2,6k (1.000)	5978	5982	54.0
			Total: 11956	Total: 11964	108.0

Specific connected load: 10.13 W/m² = 1.27 W/m²/100 lx (Ground area: 10.66 m²)

Office 1 / Calculation surfaces (results overview)



Scale 1 : 47

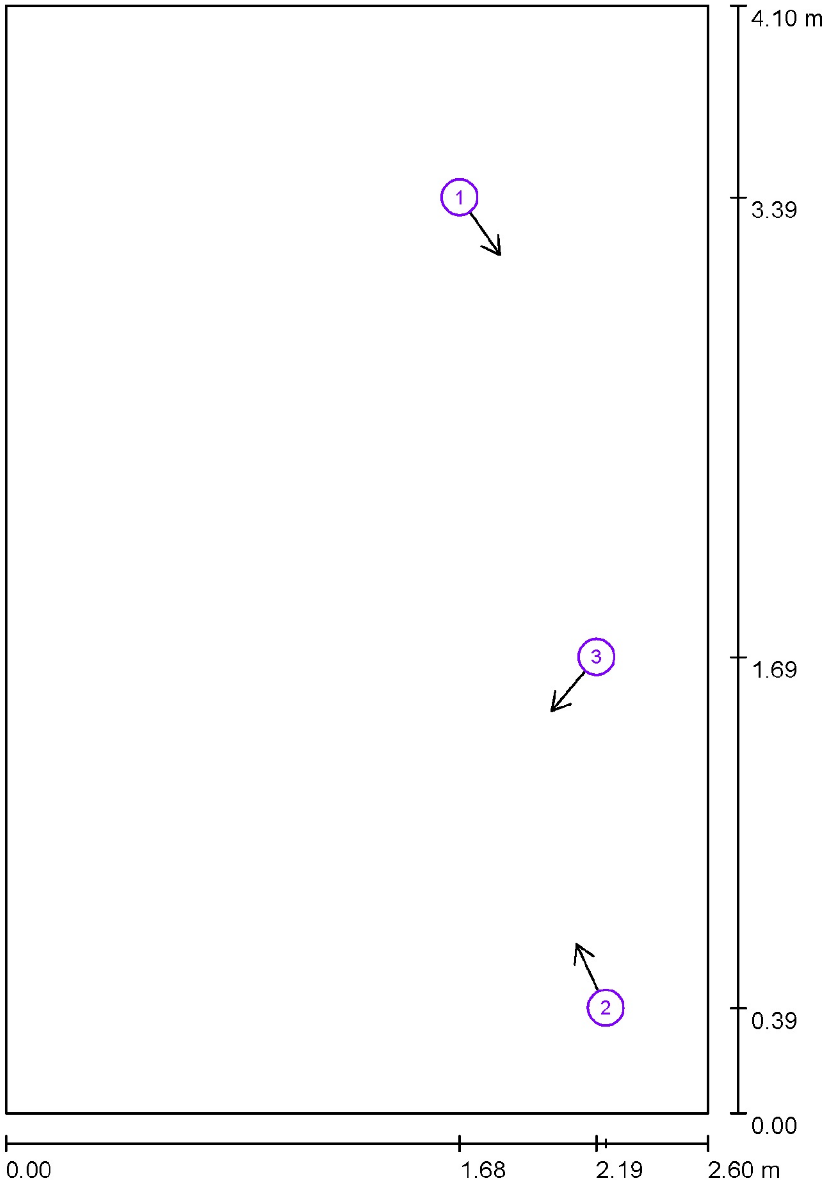
Calculation Surface List

No.	Designation	Type	Grid	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
1	Calculation surface 1	perpendicular	8 x 8	916	815	998	0.890	0.817
2	Calculation surface 2	perpendicular	8 x 8	730	570	926	0.781	0.616

Summary of Results

Type	Quantity	Average [lx]	Min [lx]	Max [lx]	u0	E_{min} / E_{max}
perpendicular	2	796	570	998	0.72	0.57

Office 1 / UGR Observer (results overview)

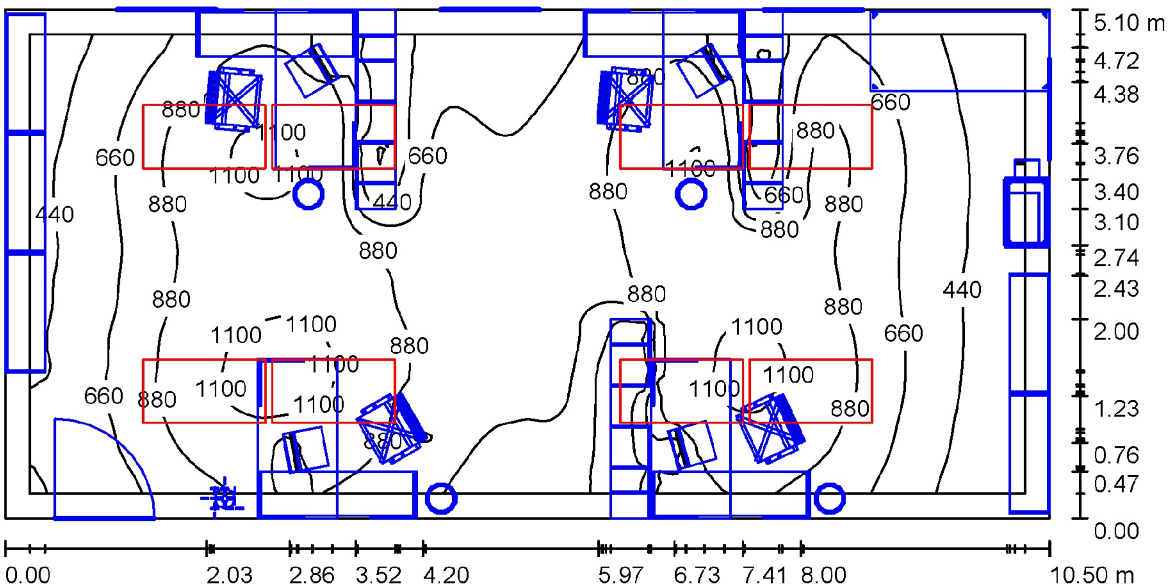


Scale 1 : 28

UGR Calculation Points List

No.	Designation	Position [m] X	Y	Z	Viewing direction [°]	Value
1	UGR Calculation Point 1	1.680	3.390	1.300	-55.0	13
2	UGR Calculation Point 2	2.222	0.390	1.200	115.0	18
3	UGR Calculation Point 3	2.188	1.689	1.200	-130.0	12

Office 2 / Summary



Height of Room: 2.600 m, Mounting Height: 2.600 m, Maintenance factor: 1.00

Values in Lux, Scale 1:76

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	744	113	1168	0.152
Floor	20	410	30	789	0.073
Ceiling	86	145	75	261	0.516
Walls (4)	68	288	6.97	863	/

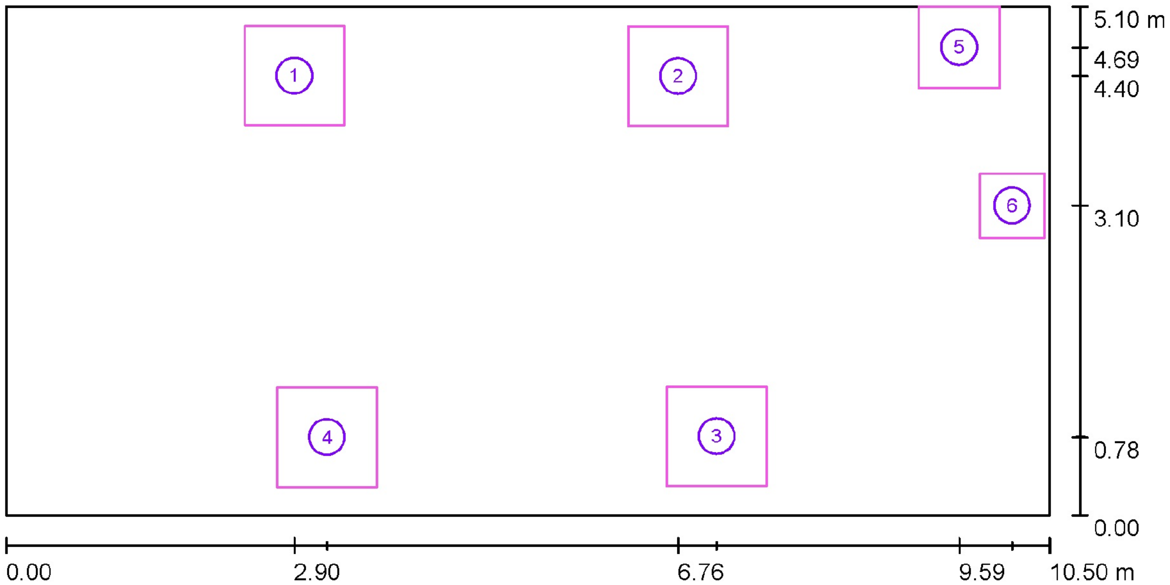
Workplane:
Height: 0.850 m
Grid: 128 x 128 Points
Boundary Zone: 0.250 m

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	8	Caverion, DurisS2,6k Caverion, DurisS2,6k Caverion, DurisS2,6k (1.000)	5978	5982	54.0
			Total: 47826	Total: 47856	432.0

Specific connected load: 8.07 W/m² = 1.08 W/m²/100 lx (Ground area: 53.55 m²)

Office 2 / Calculation surfaces (results overview)



Scale 1 : 76

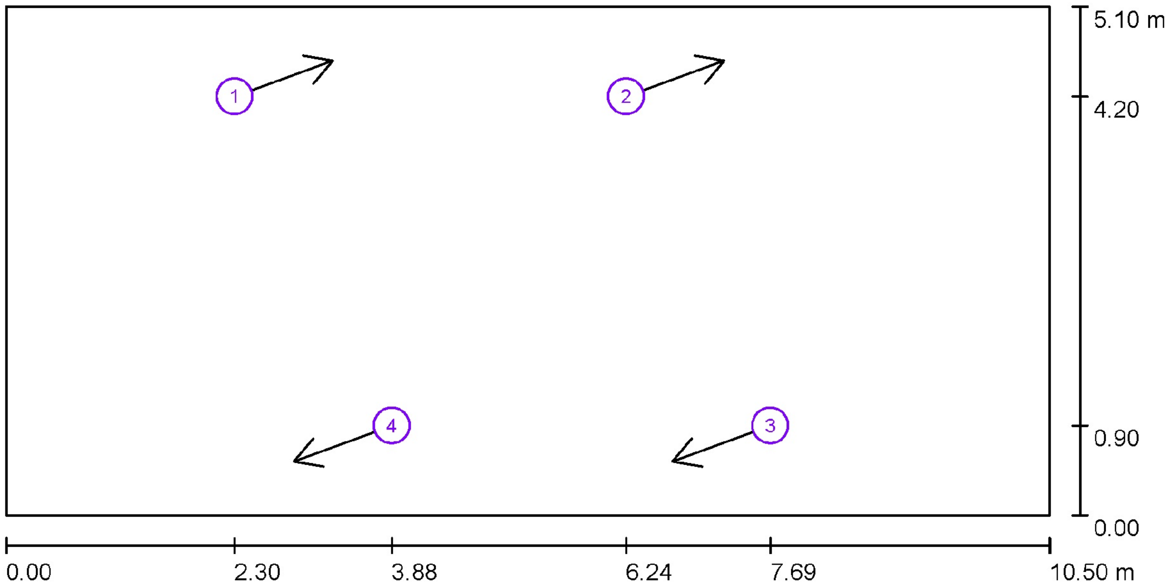
Calculation Surface List

No.	Designation	Type	Grid	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
1	Calculation surface 1	perpendicular	64 x 64	884	538	1055	0.608	0.510
2	Calculation surface 2	perpendicular	64 x 64	867	578	1032	0.667	0.560
3	Calculation surface 3	perpendicular	64 x 64	933	563	1097	0.603	0.513
4	Calculation surface 4	perpendicular	64 x 64	945	726	1105	0.768	0.656
5	Calculation surface 5	perpendicular	4 x 4	398	322	498	0.807	0.646
6	Calculation surface 6	perpendicular	4 x 4	383	352	406	0.921	0.869

Summary of Results

Type	Quantity	Average [lx]	Min [lx]	Max [lx]	u0	E_{min} / E_{max}
perpendicular	6	817	322	1105	0.39	0.29

Office 2 / UGR Observer (results overview)



Scale 1 : 76

UGR Calculation Points List

No.	Designation	Position [m] X	Y	Z	Viewing direction [°]	Value
1	UGR Calculation Point 1	2.300	4.200	1.300	20.0	17
2	UGR Calculation Point 2	6.240	4.200	1.300	20.0	16
3	UGR Calculation Point 3	7.691	0.900	1.300	-160.0	17
4	UGR Calculation Point 4	3.882	0.900	1.300	-160.0	15